National Climate Assessment Regional Technical Input Report Series

Climate Change and Pacific Islands: Indicators and Impacts

Report for the 2012 Pacific Islands Regional Climate Assessment (PIRCA)

Edited by:

Victoria W. Keener

John J. Marra

Melissa L. Finucane

Deanna Spooner

Margaret H. Smith

ISLANDPRESS

About Island Press

Since 1984, the nonprofit Island Press has been stimulating, shaping, and communicating the ideas that are essential for solving environmental problems worldwide. With more than 800 titles in print and some 40 new releases each year, we are the nation's leading publisher on environmental issues. We identify innovative thinkers and emerging trends in the environmental field. We work with world-renowned experts and authors to develop cross-disciplinary solutions to environmental challenges.

Island Press designs and implements coordinated book publication campaigns in order to communicate our critical messages in print, in person, and online using the latest technologies, programs, and the media. Our goal: to reach targeted audiences—scientists, policymakers, environmental advocates, the media, and concerned citizens—who can and will take action to protect the plants and animals that enrich our world, the ecosystems we need to survive, the water we drink, and the air we breathe.

Island Press gratefully acknowledges the support of its work by the Agua Fund, Inc., The Margaret A. Cargill Foundation, Betsy and Jesse Fink Foundation, The William and Flora Hewlett Foundation, The Kresge Foundation, The Forrest and Frances Lattner Foundation, The Andrew W. Mellon Foundation, The Curtis and Edith Munson Foundation, The Overbrook Foundation, The David and Lucile Packard Foundation, The Summit Foundation, Trust for Architectural Easements, The Winslow Foundation, and other generous donors.

The opinions expressed in this book are those of the author(s) and do not necessarily reflect the views of our donors.

Climate Change and Pacific Islands: Indicators and Impacts

Report for the 2012 Pacific Islands Regional Climate Assessment (PIRCA)

ISLANDPRESS
Washington | Covelo | London

Printed on recycled, acid-free paper

Manufactured in the United States of America

Note: This technical input document in its current form does not represent a Federal document of any kind and should not be interpreted as the position or policy of any Federal, State, Local, or Tribal Government or Non-Governmental entity

Citation: Keener, V. W., Marra, J. J., Finucane, M. L., Spooner, D., & Smith, M. H. (Eds.). (2012). *Climate Change and Pacific Islands: Indicators and Impacts. Report for The 2012 Pacific Islands Regional Climate Assessment*. Washington, DC: Island Press.

To cite specific information, please use the citation at the beginning of each chapter.

Keywords: Climate change, climate variability, Pacific islands, freshwater resources, hydrology, drought, flooding, coastal inundation, sea-level rise, adaptation, island ecosystems, climate modeling, ENSO, data and monitoring, fisheries, climate risks, downscaling, extreme events, climate change indicators, atolls, coral reefs, decision making, natural resource management

About This Series

This report is published as one of a series of technical inputs to the National Climate Assessment (NCA) 2013 report. The NCA is being conducted under the auspices of the Global Change Research Act of 1990, which requires a report to the President and Congress every four years on the status of climate change science and impacts. The NCA informs the nation about already observed changes, the current status of the climate, and anticipated trends for the future. The NCA report process integrates scientific information from multiple sources and sectors to highlight key findings and significant gaps in our knowledge. Findings from the NCA provide input to federal science priorities and are used by U.S. citizens, communities, and businesses as they create more sustainable and environmentally sound plans for the nation's future.

In fall 2011, the NCA requested technical input from a broad range of experts in academia, private industry, state and local governments, non-government organizations, professional societies, and impacted communities, with the intent of producing a better informed and more useful report in 2013. In particular, the eight NCA regions, as well as the Coastal and the Ocean biogeographical regions, were asked to contribute technical input reports highlighting past climate trends, projected climate change, and impacts to specific sectors in their regions. Each region established its own process for developing this technical input. The lead authors for related chapters in the 2013 NCA report, which will include a much shorter synthesis of climate change for each region, are using these technical input reports as important source material. By publishing this series of regional technical input reports, Island Press hopes to make this rich collection of information more widely available.

This series includes the following reports:

Climate Change and Pacific Islands: Indicators and Impacts
Coastal Impacts, Adaptation, and Vulnerabilities
Great Plains Regional Technical Input Report
Climate Change in the Midwest: A Synthesis Report for the National Climate Assessment
Climate Change in the Northeast: A Sourcebook
Climate Change in the Northwest: Implications for Our Landscapes, Waters, and Communities
Oceans and Marine Resources in a Changing Climate
Climate of the Southeast United States: Variability, Change, Impacts, and Vulnerability
Assessment of Climate Change in the Southwest United States

Electronic copies of all reports can be accessed on the Climate Adaptation Knowledge Exchange (CAKE) website at *www.cakex.org/NCAreports*. Printed copies and e-book versions are available for sale on the Island Press website at *www.islandpress.org/NCAreports*.

About This Report

Climate Change and Pacific Islands: Indicators and Impacts is a report developed by the Pacific Islands Regional Climate Assessment (PIRCA) aimed at assessing the state of knowledge about climate change indicators, impacts, and adaptive capacity of the Hawaiian archipelago and the US-Affiliated Pacific Islands (USAPI). The PIRCA is a collaborative effort engaging federal, state, and local government agencies, non-government organizations, academia, businesses, and community groups to inform and prioritize their activities in the face of a changing climate.

The immediate focus has been on bringing together almost 100 scientific experts and practitioners to generate an integrated report to provide a regional contribution to the National Climate Assessment (NCA), which is conducted under the United States Global Change Research Act of 1990. The PIRCA report examines the adaptive capacity of Pacific Island communities regarding climate change effects on freshwater availability and quality; regional and community economies; urbanization, transportation, and infrastructure vulnerabilities; ecosystem services; ocean resource sustainability and coastal zone management; and cultural resources.

The initial PIRCA activities were conducted August 2011 through February 2012 and included multiple dialogues and three workshops to facilitate sharing, analyzing, and reporting on scientific consensus, knowledge gaps, sectoral needs, and adaptive capacity for addressing the changing climate. The material presented in this report is based largely on published research. The report was reviewed and approved by the PIRCA Steering Committee, and workshop participants were invited to comment on the draft report. Several reviewers independent of the PIRCA process also provided comments.

Partners

Primary oversight of the PIRCA is being carried out jointly by representatives from the Pacific Regional Integrated Sciences and Assessments (Pacific RISA) program (funded by the US National Oceanic and Atmospheric Administration, NOAA, and supported through the East-West Center); NOAA's National Environmental Satellite, Data, and Information Service (NESDIS) and National Climatic Data Center (NCDC); the Pacific Climate Information System (PaCIS); and the Pacific Islands Climate Change Cooperative (PICCC). Other key contributors include the NOAA National Ocean Service; NOAA Pacific Services Center; NOAA Pacific Islands Fisheries Science Center; NOAA Center for Operational Oceanographic Products and Services; NOAA Coastal Storms Program; NOAA Coastal Services Center; NOAA National Marine Fisheries Service; Pacific Risk Management ʻOhana (PRiMO); United States Geological Survey Pacific Islands Water Science Center; United States Fish and Wildlife Service; University of Hawaiʻi (UH) School of Ocean and Earth Science and Technology Department of Oceanography; UH International Pacific Research Center; UH Sea Level Center; UH Sea Grant and the Center for Island Climate Adaptation and Policy; University of Guam Water and Environmental Research Institute; and the Western Regional Climate Center.

This report represents the beginning of a sustained process of assessment and information exchange among scientists, businesses, governments, and communities in the Pacific Islands region. We anticipate that in conjunction with other collaborative regional assessment efforts, this report will provide guidance for decision makers wanting to better understand how climate variability and change impact the Pacific Islands region and its peoples.

Organization of this Report

Specific chapters of the report provide:

- An overview of the Pacific Islands region, including regional geology, island communities and environments, climate variability, and climate change indicators, projections, and impacts (Chapter 1)
- A description of historical trends, projections, and impacts related to freshwater and drought (Chapter 2), sea-level rise and coastal inundation (Chapter 3), and marine, freshwater, and terrestrial ecosystems (Chapter 4)
- A discussion of conclusions (Chapter 5)

Additional details on aspects of the PIRCA process are contained in appendices that describe the Core Scientific Team, Steering Committee, workshops, and participants' evaluations of the workshops.

This report necessarily explores only a small subset of the range of potential climate impacts, due to resource and time constraints. Future assessments by the federal government, individual jurisdictions, and regional and local organizations will deepen our understanding of climate change indicators, impacts, and needed solutions.

Acknowledgments

Funding for the project was provided by the NOAA Climate Program Office for the Pacific Regional Integrated Sciences and Assessments (RISA) program (Grant #NA100AR4310216). Additional funding was provided through NOAA's NESDIS and NCDC and the NOS Coastal Storms Program. The Pacific Islands Climate Change Cooperative and the Pacific Islands Fish and Wildlife Office sponsored the Ecosystems workshop and additionally sponsored some underlying research and analysis on marine ecosystems. The editors and authors extend special acknowledgment to the following technical experts for their time and effort in providing thorough reviews of this report: Dan Cayan (University of California San Diego; US Geological Survey), Keith Ingram (University of Florida), David Kaplan (University of Florida), Kathleen McInnes (Commonwealth Scientific and Industrial Research Organisation, Australia), Stuart J. Muller (University of Florida), and Jonathan Price (University of Hawaii at Hilo). We also thank Lynette Kawakami (PICCC) and Michelle Ngo (NOAA) for their logistical and administrative agility; Lauren Kaiser (PICCC) for her annotated bibliography on impacts; Sidney Westley (East-West Center) for her editorial assistance; the East-West Center Publications Office for help with all phases of the report; Susan Yamamoto (Geovision) and Miguel Castrence (East-West Center) for help with figures and graphic design; and other external reviewers for their thoughtful comments. We are particularly indebted to the many experts who presented research, discussed findings, and iteratively authored and edited sections of this report.

Executive Summary

The Pacific Islands region is experiencing climate change. Key indicators of the changing climate include rising carbon dioxide in the atmosphere, rising air and sea temperatures, rising sea levels and upper-ocean heat content, changing ocean chemistry and increasing ocean acidity, changing rainfall patterns, decreasing base flow in streams, changing wind and wave patterns, changing extremes, and changing habitats and species distributions. Currently, the most vulnerable areas include low islands (atoll islands and other islands that rise only a few feet above present sea level), nearshore and coastal areas, and coral reefs. High-elevation (particularly alpine and subalpine) ecosystems are also vulnerable. The climatic changes are affecting every aspect of life. Freshwater supplies for natural systems, as well as communities and businesses, are at risk. Food security is threatened through impacts on both agriculture and fisheries. The built environment is also at risk from coastal flooding and erosion as sea levels incrementally increase. Loss of habitat for endangered species such as monk seals, sea turtles, and Laysan ducks is expected along with increased coral bleaching episodes, expansion of avian malaria to higher elevations, and changes in the distribution and survival of the areas' marine biodiversity. Over the coming decades, impacts are expected to become more widespread and more severe.

The Pacific Islands region is vast and diverse. Including the Hawaiian archipelago and the US-Affiliated Pacific Islands, the region comprises almost 2,000 islands spread across an expanse of ocean more than four times the size of the contiguous United States. These islands support about 1.9 million people, representing numerous languages and cultures. The islands attract millions of tourists every year and support a large US military presence.

The region comprises multiple terrestrial and marine ecosystems, ranging from mountainous alpine systems to abyssal environments deep under the ocean. The weather and climate across the region is characterized by its high natural variability. One example is El Niño-Southern Oscillation (ENSO), an interannual pattern that has a large influence on year-to-year variability in rainfall, sea level, and other climate variables.

Created under the auspices of the Pacific Islands Regional Climate Assessment (PIRCA), this report assesses the state of knowledge about climate change indicators, impacts, and adaptive capacity in three sub-regions: (1) the Western North Pacific (Commonwealth of the Northern Mariana Islands, Guam, Republic of Palau, Federated States of Micronesia, Republic of Marshall Islands); (2) the Central North Pacific (Hawai'i and the Northwest Hawaiian Islands); and (3) the Central South Pacific (American Sāmoa).

Key findings of this assessment suggest multiple concerns for human and natural communities in the Pacific Islands region:

- Low islands, coral reefs, nearshore and coastal areas on high islands, and high-elevation ecosystems are most vulnerable to climatic changes.
- Freshwater supplies will be more limited on many Pacific Islands, especially low islands, as the quantity and quality of water in aquifers and surface

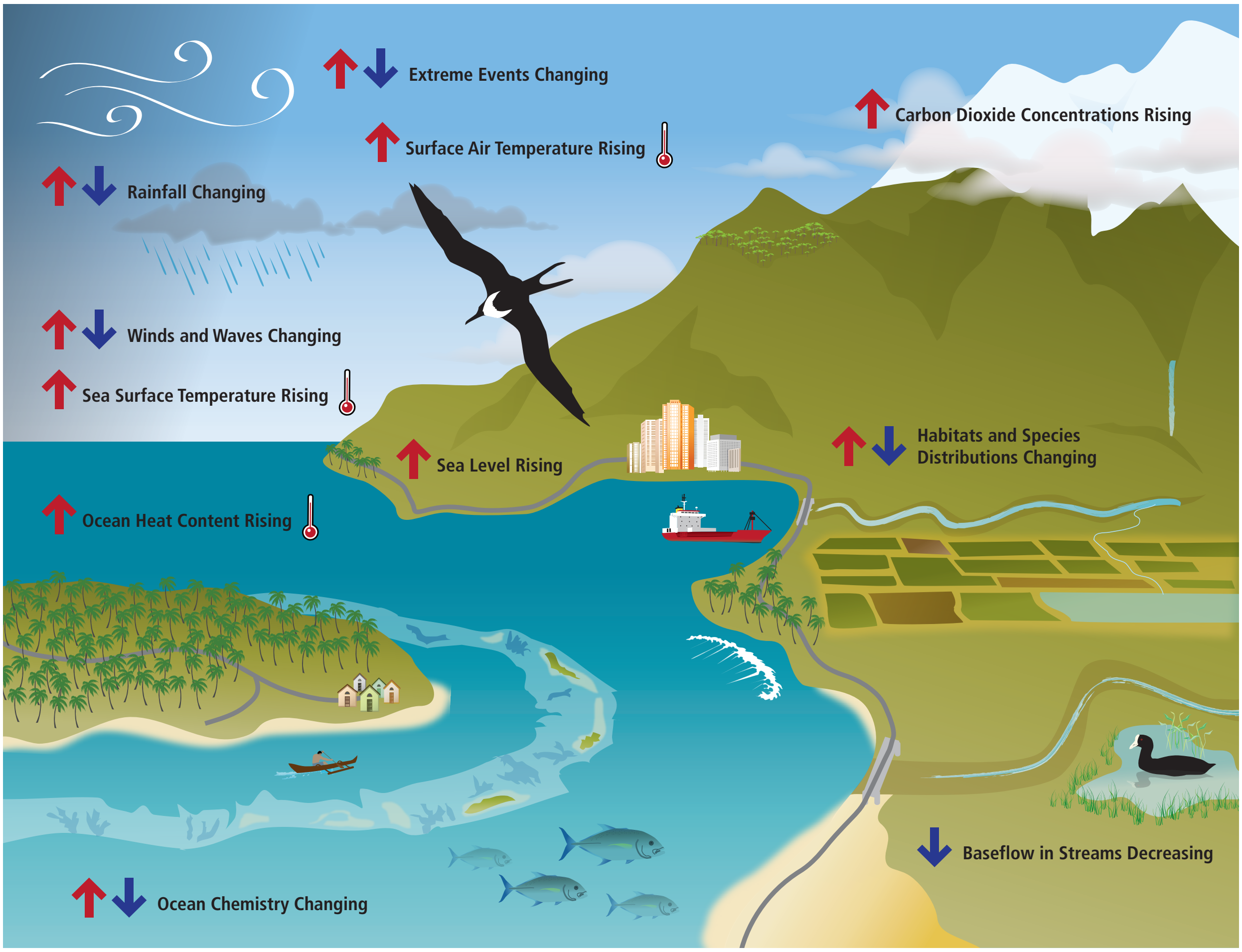


Figure A Indicators of climate change in the Pacific Islands region. (Courtesy of Susan Yamamoto, Geovision. Adapted from "Ten Indicators of a Warming World," in NOAA National Climatic Data Center, State of the Climate 2009 [report].)

catchments change in response to warmer, drier conditions coupled with increased occurrences of saltwater intrusion.

- Rising sea levels will increase the likelihood of coastal flooding and erosion, damaging coastal infrastructure and agriculture, negatively impacting tourism, reducing habitat for endangered species, and threatening shallow reef systems.
- Extreme water levels will occur when sea-level rise related to longer-term climate change combines with seasonal high tides, interannual and interdecadal sea-level variations (e.g., ENSO, Pacific Decadal Oscillation, mesoscale eddy events), and surge and/or high runup associated with storms.
- Higher sea-surface temperatures will increase coral bleaching, leading to a change in coral species composition, coral disease, coral death, and habitat loss.

- Rising ocean acidification and changing carbonate chemistry will have negative consequences for the insular and pelagic marine ecosystems; although potentially dramatic, the exact nature of the consequences is not yet clear.
- Distribution patterns of coastal and ocean fisheries will be altered, with potential for increased catches in some areas and decreased catches in other areas, but open-ocean fisheries being affected negatively overall in the long term.
- Increasing temperatures, and in some areas reduced rainfall, will stress native Pacific Island plant and animal populations and species, especially in high-elevation ecosystems, with increased exposure to non-native biological invasions and fire, and with extinctions a likely result.
- Threats to traditional lifestyles of indigenous communities in the region (including destruction of coastal artifacts and structures, reduced availability of traditional food sources and subsistence fisheries, and the loss of the land base that supports Pacific Island cultures) will make it increasingly difficult for Pacific Island cultures to sustain their connection with a defined place and their unique set of customs, beliefs, and languages.
- Mounting threats to food and water security, infrastructure, and public health and safety will lead increasingly to human migration from low islands to high islands and continental sites.

This assessment also highlights the following:

- The high interannual and interdecadal variability of the climate in the Pacific Islands region (e.g., ENSO, Pacific Decadal Oscillation) makes it difficult to discern long-term trends from short-term data.
- Many Pacific Islands lack long-term, high-quality data on rainfall, streamflows, waves, and ecosystems, and continued monitoring is needed.
- Global circulation models need to be downscaled to provide higher resolution projections for Pacific Islands to account for the influence of local topography on weather patterns and the potential impact of climate change on ecosystems.
- Sea level in the Western North Pacific has risen dramatically starting in the 1990s. This regional change appears to be largely wind-driven, is associated with climate variability, and is not expected to persist over time.
- Some islands in the region have no human inhabitants and few human impacts, offering a relatively pristine setting in which to assess the impacts of climate change on natural settings.
- Integrated biological, geochemical, and physical models are needed to improve understanding of the pressures on ecosystems and ecological responses to climate change in the Pacific Islands region.
- A better understanding of how climate change affects invasive species and their interactions with native species is needed.

- A comprehensive evaluation of the effectiveness of alternative adaptation strategies is needed to refine planning and management decisions.
- The isolation of the Pacific Islands region from the contiguous United States (and the isolation of islands from one another) presents challenges to the regional exchange of information and limits the influence of regional leaders in national and global decision-making processes.

Many of the projected impacts highlighted in this report are now unavoidable, making some degree of adaptation essential. Some jurisdictions (e.g., Hawaiʻi, American Sāmoa) are more advanced than others in developing adaptation plans and policies. Several regional coordination efforts are facilitating data collection and analysis and access to actionable information.

This report concludes that climate change confronts Pacific Islands and their communities with enormous challenges. An informed and timely response is necessary to enhance resilience to the myriad changes already occurring and those yet to come.

EXECUTIVE CHAMBERS

HONOLULU

NEIL ABERCROMBIE
GOVERNOR

March 7, 2012

Pacific Islands Regional Climate Assessment Team
East-West Center
1601 East-West Rd
Honolulu HI 96848

Dear Members of the Pacific Islands Regional Climate Assessment Team,

Proper stewardship of Hawai`i's natural resources is essential for the prosperity of future generations. To save our forests, safeguard our water sources, ensure the health of our coastal and marine resources, and perpetuate the unique cultural heritage of the Pacific, we must be confident that Hawai`i is able to withstand the impacts of climate variability and change.

The time for a long-term statewide plan for the effects of our changing climate is now. This plan should be based on the best scientific information available on potential impacts due to changes in temperature, rainfall patterns, and sea-level rise, and policymakers must have access to this information to determine the best strategy for this state.

The collaborative effort undertaken by members of the Pacific Islands Regional Climate Assessment brings together the specialized resources needed to tackle this issue. We must continue to build upon this foundation moving forward to better understand how to:

1. Preserve fresh water resources and minimize the impacts of drought;
2. Sustain aquatic and terrestrial ecosystems; and
3. Foster community resilience to the impacts of sea-level rise.

We look forward to an ongoing regional climate assessment process and appreciate your outreach to government agencies at all levels, the private sector and community groups, to engage them in this mission.

Thank you for your efforts. Your important work will contribute significantly to the prosperity of our residents and of the health of the environment upon which we depend.

Sincerely,

Neil Abercrombie
Governor, State of Hawai`i

Brian Schatz
Lieutenant Governor, State of Hawai`i

Climate Change and Pacific Islands: Indicators and Impacts

Report for the 2012 Pacific Islands Regional Climate Assessment (PIRCA)

COORDINATING LEAD EDITORS

Victoria W. Keener
East-West Center, Pacific Regional Integrated Sciences and Assessments

John J. Marra
National Oceanic and Atmospheric Administration National Climate Data Center

Melissa L. Finucane
East-West Center, Pacific Regional Integrated Sciences and Assessments

Deanna Spooner
Pacific Islands Climate Change Cooperative

Margaret H. Smith
East-West Center, Pacific Regional Integrated Sciences and Assessments

ISLANDPRESS

Washington | Covelo | London

PIRCA CORE TEAM*

Stephen Anthony
United States Geological Survey Pacific Islands Water Science Center

Tim Brown
Western Regional Climate Center, Desert Research Institute

Jeff Burgett
Pacific Islands Climate Change Cooperative

Dolan Eversole
Sea Grant, University of Hawaiʻi at Mānoa

Melissa L. Finucane
East-West Center, Pacific Regional Integrated Sciences and Assessments

Charles Fletcher
School of Ocean and Earth Science and Technology, University of Hawaiʻi at Mānoa

Kevin Hamilton
International Pacific Research Institute, University of Hawaiʻi at Mānoa

Victoria W. Keener
East-West Center, Pacific Regional Integrated Sciences and Assessments

Dawn Kotowicz
National Oceanic and Atmospheric Administration Pacific Islands Fisheries Science Center

John J. Marra
National Oceanic and Atmospheric Administration National Climate Data Center

Mark Merrifield
Joint Institute of Marine and Atmosheric Research, University of Hawaiʻi at Mānoa

Stephen E. Miller
United States Fish and Wildlife Service

Britt Parker
National Oceanic and Atmospheric Administration Coral Reef Conservation Program

Noriko Shoji
National Oceanic and Atmospheric Administration National Marine Fisheries Service

Deanna Spooner
Pacific Islands Climate Change Cooperative

Adam Stein
National Oceanic and Atmospheric Administration Pacific Services Center

William V. Sweet
National Oceanic and Atmospheric Administration Center for Operational Oceanographic Products and Services

Jean Tanimoto
National Oceanic and Atmospheric Administration Pacific Services Center

* Listed in alphabetical order

COLLABORATORS

Contents

List of Figures, Tables, and Boxes

Figures

Tables

Boxes

List of Abbreviations

Geographic

CNMI – Commonwealth of the Northern Mariana Islands

CNP – Central North Pacific sub-region (Hawaiian archipelago)

CSP – Central South Pacific sub-region (American Sāmoa)

FSM – Federated States of Micronesia

NWHI – Northwestern Hawaiian Islands

RMI – Republic of the Marshall Islands

RP – Republic of Palau

USAPI – United States-Affiliated Pacific Islands

WNP – Western North Pacific sub-region (Guam, Republic of Palau, Federated States of Micronesia, Commonwealth of the Northern Mariana Islands, Republic of the Marshall Islands)

Technical

AL – Aleutian Low

AR4 – Fourth Assessment Report (by the Intergovernmental Panel on Climate Change)

AUV – autonomous underwater vehicle

CDDs – consecutive dry days

CMIP3 – Coupled Model Intercomparison Project Phase 3

ECV – essential climate variables

EEZ – exclusive economic zone

ENSO – El Niño-Southern Oscillation

ERSST – Extended Reconstructed Sea-Surface Temperatures

ETC – extra-tropical cyclones

EUC – Equatorial Undercurrent

GCM – global climate model

GHG – greenhouse gases

GIA – glacial isostatic adjustment

GPS – global positioning system

HRI – Hawaiʻi Rainfall Index

IPO – Interdecadal Pacific Oscillation

ITCZ – Intertropical Convergence Zone

JASL – Joint Archive for Sea Level

MJO – Madden-Julien Oscillation

MNM – Marine National Monument

MSL – mean sea level

NEC – North Equatorial Current

NECC – North Equatorial Counter Current

NPGO – North Pacific Gyre Oscillation

NPH – North Pacific High

NTDE – National Tidal Datum Epoch

PDO – Pacific Decadal Oscillation

SAT – surface air temperature

SEC – South Equatorial Current

SLP – sea-level pressure

SLR – sea-level rise

SOI – Southern Oscillation Index

SPCZ – South Pacific Convergence Zone

SSH – sea-surface height

SST – sea-surface temperature

TWI – trade wind inversion

WRF-ARW – Advanced Research Weather Research and Forecasting model

Institutional

ACECRC – Antarctic Climate and Ecosystems Cooperative Research Centre

BOM – Bureau of Meteorology

CIRES – Cooperative Institute for Research in Environmental Sciences

COOPS – Center for Operational Oceanographic Products and Services

CRCP – Coral Reef Conservation Program

CRMO – Coastal Resources Management Office

CSC – Coastal Services Center (NOAA)

CSIRO – Commonwealth Scientific and Industrial Research Organisation

DOD – US Department of Defense

DMWR – Department of Marine and Wildlife Resources

DRI – Desert Research Institute

ESRL – Earth System Research Laboratory

FEMA – US Federal Emergency Management Agency

GCN – Global Core Network

GCOS – Global Climate Observing System

GEOSS – Global Earth Observation System of Systems

GLOSS – Global Sea Level Observing System

GRACE – Gravity Recovery and Climate Experiment project

HOT – Hawaiʻi Ocean Time-series program

ICAP – Center for Island Climate Adaptation and Policy

IPCC – Intergovernmental Panel on Climate Change

IPRC – International Pacific Research Institute

JIMAR – Joint Institute of Marine and Atmospheric Research

NCA – National Climate Assessment

NCDC – National Climatic Data Center

NESDIS – National Environmental Satellite, Data, and Information Service

NGS – National Geodetic Survey

NMFS – National Marine Fisheries Service

NOAA – National Oceanic and Atmospheric Administration

NODC – National Oceanographic Data Center

NOS – National Oceanographic Service

NPS – National Park Service

NRC – National Research Council

NRCS – Natural Resources Conservation Service

NWLON – National Water Level Observation Network

NWS – National Weather Service

Pacific RISA – Pacific Regional Integrated Sciences and Assessments

PaCIS – Pacific Climate Information System

PCCSP – Pacific Climate Change Science Program

PCMSC – Pacific Coastal and Marine Science Center

PEAC – Pacific ENSO Applications Climate Center

PICCC – Pacific Islands Climate Change Cooperative

PIFSC – Pacific Islands Fisheries Science Center

PIRCA – Pacific Islands Regional Climate Assessment

PIWSC – Pacific Islands Water Science Center

PRiMO – Pacific Risk Management ʻOhana

PRO – Protection Restoration Office

PSC – Pacific Services Center

SERDP – Strategic Environmental Research and Development Program

SOEST – School of Ocean and Earth Science and Technology

SPC SOPAC – Secretariat of the Pacific Community Applied Geoscience and Technology Division

SPREP – Secretariat of the Pacific Regional Environment Programme

UHSLC – University of Hawaʻi Sea Level Center

USACE – United States Army Corps of Engineers

USFS – United States Forest Service

USFWS – United States Fish and Wildlife Service

USGCRP – United States Global Change Research Program

USGS – United States Geological Survey

WERI – Water and Environmental Research Institute of the Western Pacific

WFO – Weather Forecast Office

WPFMC – Western Pacific Regional Fishery Management Council

WRCC – Western Regional Climate Center

Chapter 1

Pacific Islands Region Overview

COORDINATING LEAD AUTHORS*

Melissa L. Finucane (East-West Center, Pacific RISA), Victoria W. Keener (East-West Center, Pacific RISA), John J. Marra (NOAA NCDC), Margaret H. Smith (East-West Center, Pacific RISA)

CASE STUDY CONTRIBUTORS*

Maxine Burkett (ICAP), Victoria W. Keener (East-West Center, Pacific RISA), Margaret H. Smith (East-West Center, Pacific RISA), Noriko Shoji (NOAA NMFS)

CONTRIBUTORS*

Jeff Burgett (PICCC), Miguel Castrence (East-West Center), Howard Diamond (NOAA NCDC), Stanton Enomoto (PICCC), Lucas Fortini (PICCC), Kevin Hamilton (IPRC, University of Hawaiʻi at Mānoa), Dawn Kotowicz (NOAA PIFSC), Kenneth E. Kunkel (NOAA NCDC, North Carolina State University), Rachel L. Miller (East-West Center, Pacific RISA), Stephen E. Miller (USFWS), Britt Parker (NOAA CRCP), Deanna Spooner (PICCC), Adam Stein (NOAA PSC), Laura E. Stevens (NOAA NCDC, North Carolina State University)

*LISTED IN ALPHABETICAL ORDER

The findings and conclusions in this article are those of the author(s) and do not necessarily represent the views of the US Fish and Wildlife Service.

This Chapter should be cited as:
Finucane, M. L., Marra, J. J., Keener, V. W., & Smith, M. H. (2012). Pacific Islands Region Overview. In V. W. Keener, J. J. Marra, M. L. Finucane, D. Spooner, & M. H. Smith (Eds.), *Climate Change and Pacific Islands: Indicators and Impacts*. Report for the 2012 Pacific Islands Regional Climate Assessment (PIRCA). Washington, DC: Island Press.

Region profile

The Pacific Islands region includes the Hawaiian archipelago and the US-Affiliated Pacific Islands (USAPI). More than 2,000 islands are distributed across millions of square miles of the Pacific Ocean. The islands are isolated, with hundreds of miles of ocean between individual islands and thousands of miles between island chains. The largest aggregate of land is the State of Hawaiʻi, with 6,423 square miles (the fourth smallest state in the US). The islands are diverse in terms of geography, climate, ecology, and culture. The ocean and its resources play a vital role in the lives and livelihoods of the peoples of the Pacific Islands region. The combined exclusive economic zones (EEZ) of the region's islands encompass more than one-half of the entire EEZ of the US, making this region of great importance not just to Pacific Islanders, but to the US as a whole. The region is home to some of the most pristine habitat in the world and possesses tremendous biodiversity; thus, it is of immeasurable value to all people on the planet.

In this report, the islands in the region are grouped into three sub-regions (Figure 1-1), with affinities in terms of geography, climate, ecology, and sociology.

- **Central North Pacific (CNP) –** This area includes the State of Hawaiʻi and the Northwestern Hawaiian Islands (Papahānaumokuākea). It represents the northern bounds of Polynesia.
- **Western North Pacific (WNP) –** This area includes the Mariana, Caroline, and Marshall island chains: Guam; Commonwealth of the Northern Mariana Islands (CNMI); Republic of Palau (RP); Federated States of Micronesia (FSM, including the states of Chuuk, Kosrae, Pohnpei, and Yap); and Republic of the Marshall Islands (RMI). This area is also referred to as Micronesia.
- **Central South Pacific (CSP) –** This area includes American Sāmoa, but consideration is given to the South Pacific in general.

Pacific Island geology and landscape

The islands of the region vary widely in terms of geologic origin. They include volcanic islands, atolls, limestone islands, and islands of mixed geologic type. The highest volcanic islands reach more than 13,000 feet, while some of the atoll islands peak at only a few feet above present sea level. The distinction between "high" islands and "low" atoll islands is essential to explain the different climates on islands and the many specialized terrestrial and marine ecosystems that have evolved, as well as the forms of human communities they currently support (Figure 1-2).

The terrain of high islands is characterized by abrupt elevation changes (mountains, sheer cliffs, steep ridges and valleys), with the altitude and size of these features varying according to the age of the island. On high islands, orographic rainfall (i.e., rain associated with or induced by the presence of mountains) can cause the island to receive much higher rainfall than the surrounding ocean and is responsible for large differences between leeward and windward rainfall. The landscape on high islands is conducive to the formation and persistence of freshwater streams and the development of soils that can support large and diverse plant and animal populations. In contrast, the low atoll

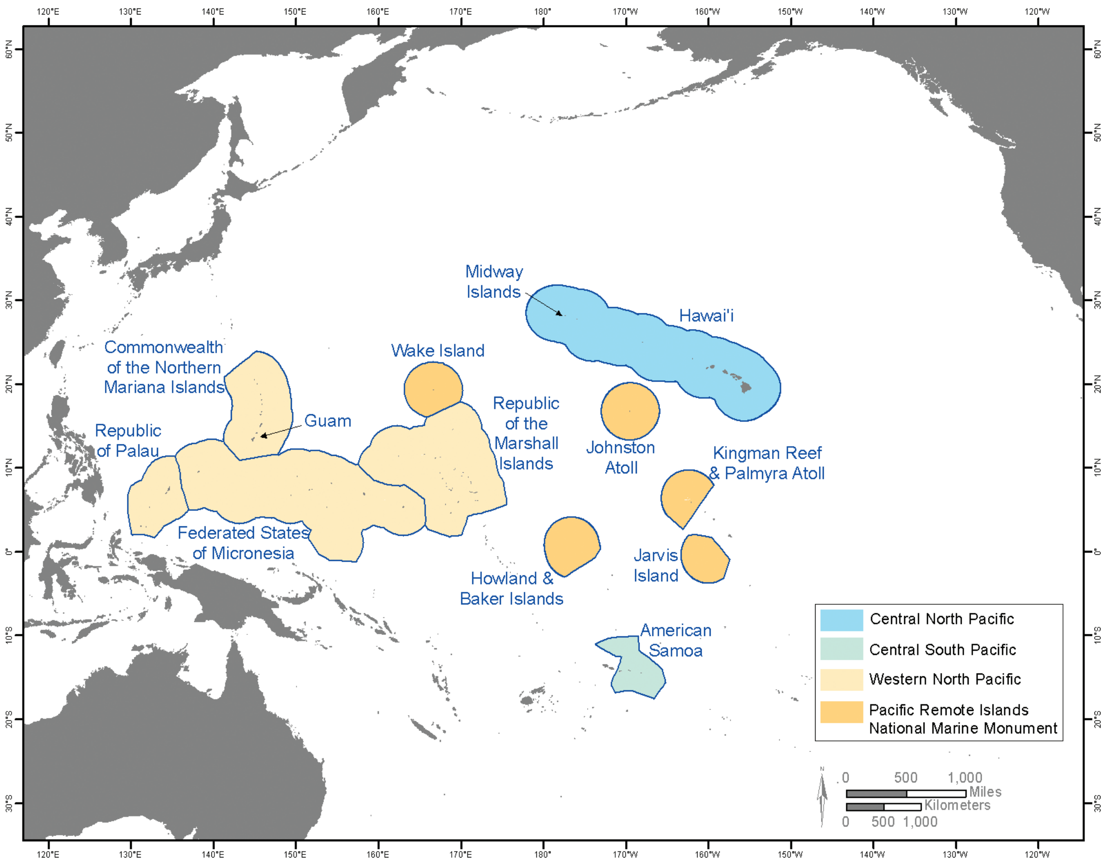


Figure 1-1 Map of the Pacific Islands region and sub-regions. The region includes the Hawaiian archipelago and the US-Affiliated Pacific Islands and comprises the Central North Pacific (blue), Western North Pacific (light orange), Central South Pacific (light green), and the islands of the Pacific Remote Island Marine National Monument (dark orange). Shaded areas indicate each island's exclusive economic zone (EEZ). (Courtesy of Miguel Castrence, East-West Center.)

islands are small and flat. They are not tall enough to generate orographic rain, and thus the amount of rainfall on low islands is close to that for the surrounding ocean. The atolls generally lack the freshwater and fertile soils that are characteristic of volcanic islands and have limited terrestrial resources. Low islands are especially prone to drought, but their varied coral reef, mangrove, and lagoon environments support rich marine ecosystems.

Because high islands have more land and freshwater resources than low islands do, they have more long-term options for responding to changes in sea level, rainfall, and other climate variables. The amount of land on volcanic islands that is flat enough for large-scale settlement, development, and agriculture is limited, however, resulting in high concentrations of population, infrastructure, and commercial development in low-lying coastal areas. Thus, while communities on high islands and low islands have somewhat similar short-term challenges associated with climate change, they have different degrees of flexibility in how they can adapt.

Figure 1-2 Examples of high and low islands. The Pacific Islands region includes high islands that may rise to more than 13,000 feet above sea level, as well as low islands that are only a few feet above present sea level. (Left: Koʻolau Mountains, © 2008 kstrebor, "Koolau Mountains windward side-HDR," used under a Creative Commons Attribution-NonCommercial-NoDerivs license. Right: Laysan Island, courtesy of Andy Collins, NOAA.)

Pacific Island peoples, governments, and economies

The Pacific Islands region includes demographically, culturally, and economically diverse communities. The first settlers of Micronesia traveled from the Philippines and Indonesia around 4,000 years ago to settle the islands of the Republic of Palau, the Mariana archipelago, and possibly Yap. A second wave of later settlers traveled approximately 2,000 years ago from southeast Melanesia, possibly the Solomon Islands, north past Kiribati, settling the Marshall Islands and then moving west through the Caroline archipelago until they met the earlier settlers in the area of western Chuuk and Yap (Rainbird, 2004). The settlement of the Polynesian region began with the early Austronesian ancestors from Taiwan approximately 5,000 years ago (Gray et al., 2009). Over thousands of years, these early settlers traveled west through Sāmoa, Fiji, and Tonga in western Polynesia before reaching the Cook, Society, Tuamoto, and Marquesas archipelagos in eastern Polynesia. The first permanent settlers of Hawaiʻi sailed north from this area, reaching the Hawaiian Islands approximately 1,200 years ago (Graves & Addison, 1995; Vitousek et al., 2004).

Contact with Europeans began with Magellan's fleet, which landed at Guam in 1521, and continued for the following four centuries under multiple colonial powers. Today, islands with ties to the US are home to nearly 1.9 million people, with most (nearly 1.4 million) living in Hawaiʻi. The majority of the island populations are composed of diverse indigenous Pacific Islander communities, intermingled with immigrants mostly from Asia, Europe, North America, Australia, and New Zealand. At least 20 languages are spoken in the region. On many islands, a large proportion of the population is rural. As rural communities often depend on agriculture and other environmentally sensitive practices, they are extremely vulnerable to weather and climate conditions.

The islands have varied histories of governance. A series of foreign countries have, at different times, governed most island chains or individual islands. Contemporary social systems throughout the region vary widely, with traditional Micronesian or Polynesian rules and institutions mixed with those adopted from colonizing countries. In Hawaiʻi and Guam, cash economies are highly developed, relatively few people rely on subsistence agriculture or fishing, and western legal systems dominate. In American Sāmoa and throughout Micronesia, traditional cultural systems govern behavior and traditional political structures are in place. Tribal systems led by chiefs have a large influence on decision making in the RMI, the FSM, and American Sāmoa (Petersen, 2009).

Pacific Island populations share a cultural value that links society and the environment. Resource management and conservation are essential for healthy, stable communities on islands with limited resources because overexploitation could damage or permanently destroy resources. A key value for survival in Hawaiʻi, for instance, is *mālama ʻāina*, which means caring for the land (Kawaharada, 2011). In general, Pacific Island cultures recognize the value and relevance of their cultural heritage and systems of traditional knowledge and customary law developed within their social, cultural, and natural contexts (e.g., Gegeo & Watson-Gegeo, 2001). At the same time, contemporary island communities reflect diverse ancestries that, over time, have blended to create new cultural values. There is an emphasis on long-term connection with lands and resources, with multigenerational attachment to places (Gegeo, 2001; Teddy, Nikora, & Guerin, 2008). Climate change threatens the physical, biological, and human elements necessary for Pacific Island cultures to sustain their co-existence and evolving relationship with a defined place and to maintain their unique set of customs, beliefs, language, traditional knowledge, objects, and built environment. This threat is due in part to the familial and divine relationships certain Pacific Island cultures have with the natural world and the implications of severed kinship ties when places, species, and practices are lost (e.g., Liliʻuokalani, 1997).

Economic indicators show a wide range within the region (Table 1-1). Tourism figures prominently in the GDP of most island jurisdictions. Hawaiʻi, for instance, welcomed almost 7 million visitors to the state in 2011, generating $12.6 billion in revenue (Hawaiʻi Tourism Authority, 2011). A large US military presence means that the defense sector is also an important source of income. Climate change threatens the ecosystems (such as forests, streams, coral reefs, and open ocean) that communities rely on for sustenance and revenue. Geographic remoteness means that the cost of transport has a profound influence on island economies.

The isolation of the communities of the region, from one another and from the rest of the world, has led to the development of technological and cultural strategies for responding to events such as typhoons and large inter-annual variability in rainfall. Historically, settlement patterns, crop diversity, food storage and preservation techniques, and strategies for intercommunity cooperation have evolved in different ways to cope with local conditions on each island (Barnett & Campbell, 2010). More recently, the recurrence of drought in the FSM has prompted systems of rationing and strategies for importing water (UN Office for the Coordination of Humanitarian Affairs, 1998).

Although isolation has proved helpful in the development of adaptations that are highly specific to local needs, it has limited the gathering and exchange of regional information that could support and enhance local adaptation strategies. Scientific study is inhibited by the labor and costs required to maintain climate monitoring systems in such remote locations. At the national and global levels, decisions on adaptation strategies are made without good information from the region. Conversely, distribution of national and global scientific and policy information around the region must be translated into multiple languages.

Table 1-1: Economic and demographic indicators for Hawaiʻi and the US-Affiliated Pacific Islands

	Population	Adjusted GDP	GDP per capita	Major income sources	Governance
Hawaiʻi	1,374,810 (2011 est.)	$66.7 billion (2011 est.)	$48,500 (2011 est.)	Tourism, US military, construction	US state
CNMI	46,050 (2011 est.)	$900 million (2000 est.)	$12,500 (2000 est.)	US payments, tourism, subsistence agriculture and fishing	Commonwealth in political union with the US
FSM	106,836 (2011 est.)	$238.1 million (2008 est.)	$2,200 (2008 est.)	US payments as part of their Compact of Free Association agreement, subsistence agriculture and fishing	Constitutional government in free association with the US
Guam	183,286 (2011 est.)	$2.5 billion (2005 est.)	$15,000 (2005 est.)	US military, tourism (primarily from Japan), construction	Organized, unincorporated territory of the US
RMI	67,182 (2011 est.)	$133.5 million (2008 est.)	$2,500 (2008 est.)	US military, US payments as part of their Compact of Free Association agreement, subsistence agriculture and fishing	Constitutional government in free association with the US
RP	20,956 (2011 est.)	$164 million (2008 est.)	$8,100 (2008 est.)	Tourism, subsistence agriculture, and fishing	Constitutional government in free association with the US
American Sāmoa	67,242 (2011 est.)	$575.3 million (2007 est.)	$8,000 (2007 est.)	US payments, tuna fishing and processing	Unorganized, unincorporated territory of the US

Note: Adjusted GDP (purchasing power parity) and GDP per capita show a wide range within the region. All data in this table are from the *World Factbook* (2011), except for the Hawaiʻi data, which comes from the Hawaiʻi State Department of Business, Economic Development & Tourism (2011).

Several region-wide initiatives aim to foster communication and information sharing on climate-related topics. These include the Pacific Climate Information System (*http://www.pacificcis.org/*), Pacific Regional Integrated Sciences and Assessments program (*http://www.pacificrisa.org/*), Pacific Islands Climate Change Cooperative (*http://www.piccc.net/*), Pacific Risk Management O`hana (*http://collaborate.csc.noaa.gov/PRiMO/*), and the Secretariat of the Pacific Regional Environment Programme's Pacific Climate Change Roundtable and Pacific Adaptation to Climate Change project (*http://www.sprep.org/pacc-home*). The Micronesia Challenge represents a similar effort, with a focus on the Western North Pacific sub-region (*http://www.micronesiachallenge.org/*).

Pacific Island ecosystems

The region is home to unique natural communities of global significance. It is characterized by a variety of linked and interacting ecosystems that range from alpine shrublands to wet forests, mountain streams to mangroves, and coral reefs to deep-sea trenches that extend across the world's largest ocean. The same ocean currents and winds that guided human expansion and colonization of the islands also served to transport animals, plants, and microorganisms across great distances. The isolated nature of the islands has led to ecosystems that are unique, diverse, and relatively pristine, with extremely large numbers of endemic species (Pratt & Gon, 1998; Sadler, 1999; Ziegler, 2002). Yet the region's rich biodiversity is fragile. In addition to climate change, human-related impacts from agricultural and infrastructure development mean that more than 400 island species are listed under the Endangered Species Act. Many of these species are found in a network of protected areas, including 22 National Wildlife Refuges, 11 National Park units, 4 Marine National Monuments, 2 National Marine Sanctuaries, and state, territorial, local, and private conservation areas. Sustaining the health of ocean and coastal ecosystems and their accompanying resources is vital to island life.

Box 1-1

Marine national monuments in the Pacific Islands region

In January 2009, President George W. Bush declared three Marine National Monuments (MNMs) in the Western Pacific: the Pacific Remote Islands, Marianas Trench, and Rose Atoll. This followed the creation of the Papahānaumokuākea Marine National Monument in 2006. These marine areas are home to a large diversity of species, including many threatened and endemic species. They include unique and diverse features such as the Ring of Fire (one of the most volcanically active areas on earth), which is a vast array of seamounts and underwater hydrothermal vents and volcanoes, extensive coral reef habitats, and the deepest marine trench on the planet. Monument designation called for a stop to commercial fishing and for the development of Management, Research and Exploration Plans for the Monuments.

Overall management of the Monuments is shared between the Department of the Interior and the National Oceanic and Atmospheric

Box 1-1 (Continued)

Administration (NOAA). The Department of the Interior has delegated its responsibility to the US Fish and Wildlife Service (USFWS). Collaborative planning and partnerships are crucial to the long-term protection of these diverse and abundant marine resources, so NOAA and the USFWS are seeking input from stakeholders regarding the development of the Management, Research and Exploration Plans. NOAA and USFWS will work with partners to understand and protect the unique natural and cultural resources within the Monuments through the advancement of scientific research, exploration, and public education.

The **Papahānaumokuākea MNM** comprises 140,000 square miles of the Pacific, approximately 250 nautical miles northwest of Hawai'i, and includes the Northwestern Hawaiian Islands and Midway Islands. In 2010, Papahānaumokuākea was recognized as a UNESCO World Heritage Site for its remarkable collection of natural and cultural resources. Over 7,000 marine species are supported by the extensive coral reefs in the area, with 25% of these species not found elsewhere. Papahānaumokuākea is also the world's largest tropical seabird nesting area: over 5.5 million seabirds build their nests there each year, with 14 million residing there seasonally. Important cultural and archeological artifacts are also located on the islands.

The **Mariana Trench MNM** encompasses 96,714 square miles, including waters and submerged lands around the three northernmost Mariana Islands; submerged lands of designated volcanic sites; and submerged lands of certain portions of the trench. The Mariana Trench contains some of the deepest ocean environments on earth and is a refuge for seabirds, sea turtles, unique coral reefs, and an immense diversity of seamount and hydrothermal vent life. Photosynthetic and chemosynthetic communities coexist within the monument in Maug Crater, one of only a few places on Earth where this is known to occur. USFWS and NOAA are to consult with the Secretary of Defense, the US Coast Guard, and the government of the Commonwealth of the Northern Mariana Islands in managing the monument.

The **Pacific Remote Islands MNM** includes 82,129 square miles of waters around Wake, Baker, Howland, and Jarvis Islands, Johnson Atoll, Kingman Reef, and Palmyra Atoll. These areas support a large number of nesting seabirds and coral reefs, and they contain hundreds of thriving fish species, large apex predators, and endangered turtles.

The **Rose Atoll MNM** encompasses 13,436 square miles of the ocean, located 130 nautical miles east-southeast of American Sāmoa. The atoll contains an abundance of species that have faced depletion elsewhere. It is an important nesting area for the threatened green sea turtle and endangered hawksbill sea turtle. The Rose Atoll Monument is undergoing public review for consideration of being added to the Fagatele Bay National Marine Sanctuary. The government of American Sāmoa will be a cooperating agency in development of a monument management plan.

Box 1-1 Photo 1 Bluefin Trevally in Papahānaumokuākea Marine National Monument. (Courtesy of James Watt, USFWS.)

Box 1-2

Ecosystems of the Pacific Islands region

Alpine and Subalpine

Distribution: *Central North Pacific*

Restricted to three volcanic mountains in the Hawaiian archipelago—Mauna Kea (13,796 ft.) and Mauna Loa (13,680 ft.) on the island of Hawai'i, and Haleakalā (10,023 ft.) on the island of Maui. Characterized by seasonal snow but otherwise arid conditions, low temperatures, sparse vegetation, and specialist endemic fauna. The subalpine zone often is demarcated by the upper treeline of montane forests.

Box 1-2 Photo 1 The threatened, endemic 'ahinahina or Haleakalā silversword (*Argyroxiphium sandwicense subsp. macrocephalum*) in full bloom on Maui, Hawaiian Islands. (Courtesy of NPS.)

Montane Forest (wet, mesic, and dry)

Distribution: *Regional*

Montane forests are found on high islands in the Hawaiian, Samoan, and Mariana archipelagos and are distinguished by rainfall and soil type. Rainfall ranges from 400+ inches annually in wet forests and high-elevation bogs (Maui and Kaua'i Islands, Hawaiian archipelago) to less than 50 inches annually in dry forests, often located on the leeward side of islands. Montane forests support tens of thousands of native species, many unique to a particular island or area within an island.

Box 1-2 Photo 2 The endemic 'i'wi or Hawaiian Honeycreeper (*Vestiaria coccinea*) perched on an endemic lobelia (*Lobelia grayana*) at the Waikamoi Preserve, Island of Maui. (Courtesy of Daniel W. Clark.)

Lowland Forests, Shrublands, and Grasslands (wet, mesic, and dry)

Distribution: *Regional*

Lowland forests, shrublands, and grasslands are found on high and low islands throughout the region and experience a large range in rainfall, most often associated with location on windward (wet) and leeward (dry) sides of islands.

Box 1-2 Photo 3 The fruit bat, or flying fox, inhabits lowland, coastal, and mangrove forests in the Central South and Central Western Pacific. Pictured is the Samoan species (*Pteropus samoensis*). (Courtesy of NPS.)

Box 1-2 (Continued)

Lava Pioneer (all elevations)

Distribution: *Hawaiian Islands*

Lava pioneer, unique to the island of Hawai'i, is characterized by lava flows where soil has yet to form. It is quickly colonized by "pioneer" plants and animals.

Box 1-2 Photo 4 The endemic 'ōhi'a lehua (*Metrosideros polymorpha*) is found in montane, lowland, and lava pioneer ecosystems throughout the Hawaiian Islands. (Courtesy of D. Spooner.)

Streams (all elevations)

Distribution: *Regional, high islands*

Streams provide freshwater habitats on all high islands in the region and support a number of native and endemic fish, shrimp, invertebrates, and aquatic plants.

Coastal Plain

Distribution: *Regional*

Coastal plains are found on most low islands, some elevated coral atolls, and most high islands. They often harbor both wet and dry forests and/or wetlands, and the transition from coastal plain to strand (beach) or mangrove is at times indistinguishable. Coastal plains are important areas for traditional agriculture.

Coastal Wetlands

Distribution: *Regional*

Coastal wetlands on high and low islands support a variety of freshwater, brackish, and saltwater plant and animal communities, provide crucial habitat for resident and migratory waterbirds, and support traditional agriculture.

Coastal Strand

Distribution: *Regional*

The coastal strand, or dunes, marks the boundary between terrestrial and marine realms and is found on all islands and atolls in the region. Few intact coastal strand areas remain on inhabited islands due to human development pressure.

Box 1-2 Photo 5 A Hawaiian monk seal (*Monachus schauinslandi*) and red-footed boobies (*Sula sula*) resting in the Northwestern Hawaiian Islands. (Courtesy of USFWS.)

Coastal Mangroves

Distribution: *West and South Pacific*

Mangroves are native to the Western Pacific and play an important role in maintaining coastal ecosystems in Micronesia. American Sāmoa marks the easternmost range of mangroves indigenous to the Pacific.

Seagrass

Distribution: *Regional*

Seagrass meadows are important components of estuaries, bays and lagoons, fringing reef, barrier

Box 1-2 (Continued)

reef, and deepwater areas. Seagrasses are the only flowering plants that can live underwater, and they provide foraging and sheltering habitat for a variety of species.

Box 1-2 Photo 6 A giant trevally (*Caranx ignobilis*) foraging in a seagrass meadow. (Courtesy of NOAA.)

Coral Reefs

Distribution: *Regional*

Coral reefs are one of the most biologically diverse ecosystems on the planet, supporting complex communities from shallow to deep waters. Deepwater corals are some of the oldest organisms on earth, with 4,000-year-old corals identified in the Hawaiian archipelago.

Box 1-2 Photo 7 The coral reefs in American Sāmoa support a diversity of species, including the beaded sea anemone (*Heteractic aurora*). (Courtesy of Paul Brown, NPS.)

Pelagic

Distribution: *Regional*

The pelagic (open-ocean) realm dominates the Pacific Islands region, supporting a diverse web of organisms, including microscopic plankton, fishes, marine reptiles, marine mammals, and seabirds.

Box 1-2 Photo 8 Whales are the largest inhabitants of the pelagic (open) ocean areas of the Pacific Islands. Pictured here are humpback whales (*Megaptera novaeangliae*). (Courtesy of NOAA.)

Undersea Volcanoes and Thermal Vents

Distribution: *Regional*

Undersea volcanoes and thermal vents support unusual life forms that thrive in complete darkness in highly acidic and boiling water.

Abyssal

Distribution: *Regional*

At the bottom of the ocean is the abyssal zone, supporting deep benthic communities of bacteria, shellfish, fish, and other organisms. The Mariana Trench is the deepest point on Earth (10,994 meters), which is deeper than the height of Mount Everest above sea level.

Weather and climate

Because of its proximity to the Equator, the Pacific Islands region experiences relatively small seasonal variations in air temperature. In contrast, rainfall varies widely by season and location. The islands of the region all have distinct wet and dry seasons that loosely correspond to winter and summer months. However, the timing, duration, and intensity of these seasons, like the weather and climate in general, vary due to the combinations of atmospheric and ocean circulation patterns that are unique to each sub-region.

The dominant “centers of action” with respect to atmospheric circulation in the Central North Pacific are the North Pacific High (NPH), the Aleutian Low (AL), and the Intertropical Convergence Zone (ITCZ) (see Appendix A). In the Western North Pacific, important elements include the East Asian and Western Pacific monsoon system. In the Central South Pacific, in particular the area around American Sāmoa, the South Pacific Convergence Zone (SPCZ) is highly influential. The oceanic circulation of the region is dominated by the westward-flowing tropical branches of the North and South Pacific Gyre systems, namely the North and South Equatorial Currents (NEC, SEC) and, to a lesser degree, the eastward-flowing North Equatorial Counter Current (NECC) and the cold Equatorial Undercurrent (EUC) that flows eastward beneath the SEC at the equator and feeds the equatorial upwelling within the eastern tropical Pacific. The role of the ocean in controlling weather and climate cannot be underestimated. Sea-surface temperature, for example, affects tropical cyclone formation. The ocean (and the coupled atmospheric as well as chemical and biological) system redistributes heat from the tropics to the poles (as well as moisture, dissolved oxygen, nutrients, and so forth). It also serves as a global sink for heat and carbon dioxide.

Central North Pacific

Weather and climate in the Central North Pacific sub-region (CNP) are strongly influenced by the NPH and associated northeast trade winds, which blow about 75% of the year. During the winter in the northern hemisphere, the NPH is located closer to the equator and on average is smaller, weaker, or even absent (Figure 1-3). The winter is also when the AL is large, most intense, and located farther south, with the associated prevailing winds from the west reaching as far south as 28°N. It is during this time that extra-tropical cyclones regularly spin-up off the AL and drop into the prevailing west winds. These storms lead to the high waves that reach the northern shores of the Hawaiian Islands. During the northern hemisphere summer, the AL is located farther north and is impermanent or nonexistent, whereas the NPH reaches its peak size and northernmost position. Trade winds, blowing from the east, extend correspondingly, on average to 35°N. The frequency of rainfall associated with the trade winds also increases (NOAA Pacific Storms Climatology Products, n.d.).

Western North Pacific

Weather and climate in the Western North Pacific sub-region (WNP) are shaped by its proximity to the NPH, associated trade winds, and the monsoon trough, a local manifestation of the ITCZ, a zone of converging winds and relatively high rainfall. The position of the monsoon trough varies seasonally. From May to October, it moves through the

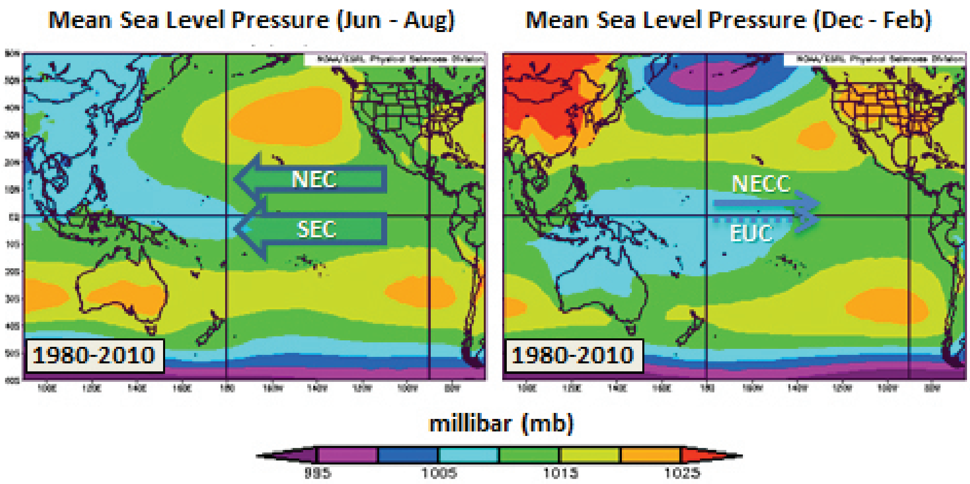


Figure 1-3 Northern hemisphere summer (June–August) versus winter (December–February) plots of the annual average atmospheric pressure at sea level (SLP). In June–August (left), the area of strong average high pressure (orange) that extends across the CNP corresponds to the NPH. In December–February (right), the area of strong average low pressure (purple) centered on the Gulf of Alaska corresponds to the AL. (Courtesy of NOAA ESRL Physical Sciences Division.)

sub-region, bringing each island its rainy season. The trade winds are stronger and last longer in the northern and eastern parts of the sub-region (closest to their origin in the NPH). They can also generate high surf (NOAA Pacific Storms Climatology Products, n.d.). The trade winds are more persistent during the winter months and less persistent during the summer months when the monsoon trough expands, creating strong winds from the southwest (Kodama & Businger, 1998). The trade winds are most persistent in RP and the southwestern parts of the sub-region, episodic on Guam, and rarely felt in RMI to the northeast (Bridgman & Oliver, 2006; NOAA Pacific Storms Climatology Products, n.d.). The monsoon trough activity makes the WNP the most active tropical cyclone basin, with an annual average of approximately 26 cyclones reaching tropical storm strength or greater (Knapp et al., 2010).

Central South Pacific

The weather and climate of the Central South Pacific sub-region (CSP) are affected by the South Pacific Convergence Zone (SPCZ). Like the ITCZ, the SPCZ is a zone of converging winds and relatively high rainfall. Trade winds dominate from May to October, although the winds originate from subtropical high-pressure areas in the southern hemisphere instead of the NPH. Rainfall varies widely by season: approximately 75% of annual rainfall occurs from November to April, when the SPCZ is located about halfway between Western Sāmoa and Fiji. During the dry season, the SPCZ moves out of the area and often becomes weak or inactive (Australian Bureau of Meteorology & CSIRO, 2011). Heavy rainfall in this sub-region is primarily associated with tropical cyclones.

Inter-annual and interdecadal variability

High inter-annual and interdecadal variability is a characteristic feature of the climate in the Pacific Islands region. Seasonal patterns of variability are influenced by El Niño-Southern Oscillation (ENSO). ENSO is associated with changes in a number of coupled oceanic and atmospheric conditions across the Pacific, including differences in atmospheric pressures in an east-west direction along the equator through the tropics, its effect on the trade winds, sea-surface height (SSH), sea-surface temperature (SST), the position of the jet streams and storm tracks, and the location and intensity of rainfall (Wyrtki, 1975; Trenberth, 1991; IPCC, 2007; Australian Bureau of Meteorology & CSIRO, 2011). The two extremes are the warm phase (El Niño event) and the cold phase (La Niña event) (Figure 1-4). El Niño is characterized by decreased trade wind activity, which allows the warm waters gathered by the winds into the western Pacific to flow eastward. This warming is coupled with an eastward shift in convective cloudiness and rainfall. During La Niña, this pattern is reversed: stronger trade winds allow the area of cold SSTs in the eastern Pacific to become larger. Occurring roughly every 3 to 7 years with events generally persisting for 6 to 18 months, ENSO maintains a pattern that gives it a level of predictability yet retains some variability in its occurrence, magnitude, and climate consequences around the world (Cane, 2005).

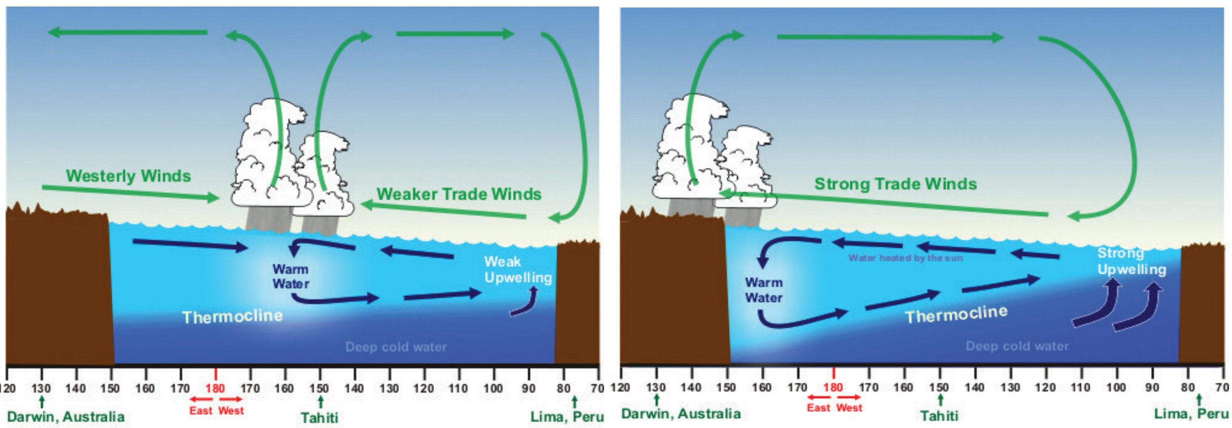


Figure 1-4 El Niño and La Niña events. During El Niño (left), the trade winds decrease, ocean water piles up off South America, the SST increases in the eastern Pacific, and there is a shift in the prevailing rain pattern from the western Pacific to the western Central Pacific. During La Niña (right), the trade winds increase, ocean water piles up in the western Pacific, the SST decreases in the eastern Pacific, and the prevailing rain pattern also shifts farther west than normal. (Courtesy of NOAA National Weather Service.)

The effects of ENSO on the region are significant (Giambelluca et al., 2011), and they vary among the sub-regions (Figure 1-5). In the CNP, weakened trade winds during El Niño events reduce rainfall and cause dry conditions throughout the Hawaiian Islands; rainfall is higher during La Niña. Elsewhere in the Pacific, the situation is more complex.

Dry conditions prevail across much of the WNP during El Niño. In the CSP, the location of the SPCZ shifts during El Niño, causing heavy rainfall or dry conditions depending on the strength of the particular event and the island location (Australian Bureau of Meteorology & CSIRO, 2011). The frequency and intensity of subtropical cyclones (hurricanes, typhoons) are also affected by ENSO (Lander, 2004; Maue, 2011). In the Western North Pacific, typhoons tend to be more intense in El Niño years (Gualdi et al., 2008).

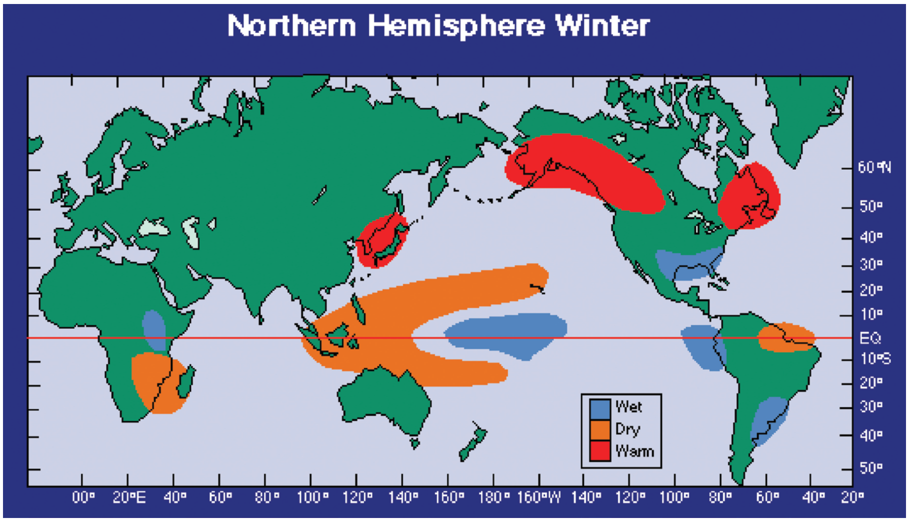


Figure 1-5 Precipitation during El Niño in the northern hemisphere winter. (Courtesy of NOAA Pacific Marine Environmental Laboratory.)

The weather and climate patterns of the region are also influenced by longer, multidecadal periods of coupled atmospheric-oceanic conditions, such as the Pacific Decadal Oscillation (PDO) (Mantua et al., 1997; D'Aleo & Easterbrook, 2010). The PDO is characterized by alternating periods of dominance of El Niño (warm phase) versus La Niña (cold phase) and corresponding changes in atmospheric circulation, ocean circulation, SST, SSH, and so forth throughout the whole Pacific Basin. These PDO phases tend to persist for 20 to 30 years (D'Aleo & Easterbrook, 2010). It is generally agreed that a warm phase of more frequent, longer, and stronger El Niños occurred from about 1976 to 1998. A shift back to the cold phase of La Niña appears to have commenced in 1999, and it is anticipated these conditions may persist for the next two or three decades. Decadal to interdecadal variability linked to the PDO is most conspicuous in the North Pacific, where fluctuations in the strength of the winter Aleutian Low pressure system co-vary with North Pacific SST (IPCC, 2007). Although nearly identical, the Interdecadal Pacific Oscillation (IPO, compared to the PDO) applies to the broader (south as well as north) Pacific (IPCC, 2007). Recently, considerable attention has focused on observed variations in ENSO at decadal time scales (Maue, 2011). Specifically, during the past two decades, in contrast to classical El Niño with eastern tropical Pacific warming, the occurrence of central Pacific warming episodes referred to as El Niño Modoki events has noticeably increased relative to classical El Niño events, which are characterized by warming of the eastern Pacific (Lee & McPhaden, 2010; Maue, 2011).

Observations and monitoring

Long-term, continuous, and high-quality observations of the environment, including chemical and biological variables as well as physical variables such as air temperature, rainfall, and sea-surface temperature, are critical for understanding the current and future state of the weather and climate in the region. "Climate-quality" data are critical not only for understanding the dynamics of natural processes but also for ensuring the accuracy of models that simulate possible and probable future impacts of climate change and variability. Because the majority of the Pacific Islands region is ocean, a robust ocean observational network is key to understanding local climatic phenomena. Land-based networks of long-term stream and rainfall gauges, as well as temperature, evapotranspiration, and wind stations, for example, are also essential.

Globally, significant progress has been made in the past 20 years in coverage and technological capability. The Global Climate Observing System (GCOS), a component of the Global Earth Observation System of Systems (GEOSS), has documented the

Box 1-3

Distinguishing climate variability from climate change in the Pacific

The Pacific Ocean covers approximately one-third of the Earth's surface and plays a significant role in determining the complex global dynamics among the ocean, atmosphere, and land systems that shape the Earth's climate. Within the Pacific Islands region, climatological prediction in the tropics, and to a lesser degree outside the tropics, is tightly linked to our ability to accurately predict tropical sea-surface temperature (SST) (Kumar & Hoerling, 1998; Goddard et al., 2001; Annamalai et al., 2011).

Tropical SST variations in the Pacific are dominated by natural short-term cycles such as El Niño-Southern Oscillation (ENSO) events (Ropelewski & Halpert, 1987; Kiladis & Diaz, 1989) and the Interdecadal Pacific Oscillation (IPO), which is the manifestation of the Pacific Decadal Oscillation (PDO) in both the southern and northern hemispheres (Meehl et al., 2009).

As a result of these short-term cycles, variability in annual rainfall for the Pacific Islands is much higher than in regions not affected by ENSO. Specifically, ENSO magnifies the magnitude of inter-annual rainfall fluctuations in the Pacific by one-third to one-half as compared to unaffected areas (Nicholls, 1988). This short-term variability obscures long-term trends and patterns in historical data resulting from climate change (Madden, 1976): signals in temperature and precipitation that are more easily detected in other areas of the globe are hidden by ENSO noise in the Pacific region. This relatively high internal climate variability results in a low signal-to-noise ratio in the region, patterns in long-term climate variables (such as temperature and precipitation) (Kumar & Hoerling 1998; Meehl et al., 2009; Deser et al., 2010b).

Although ENSO and IPO cycles make it difficult to predict future regional climate at time scales of decades to centuries, the value of global and regional climate models is that they can predict with substantial confidence how the long-term average climate will change as a result of natural and human-induced factors (Figure 1-6).

Box 1-3 (Continued)

For example, if a short-term extreme event such as a drought occurs in the future when the average climate is drier than it is currently, the net result could be a drought that exceeds similar dry conditions in the past.

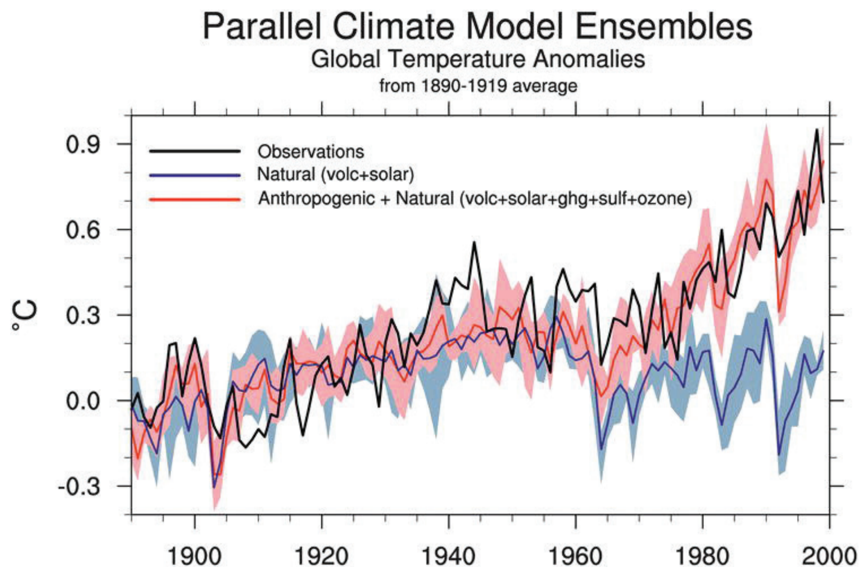


Figure 1-6 Simulated natural versus human-induced global temperature, 1890–2000. Using an ensemble of four climate models, scientists can differentiate between human-induced trends and natural trends in long-term global climate variables. Here, the observed change in global annual air temperature (black line) is compared to the predicted range of air temperature with only natural climate variability (blue line with blue shading) and the predicted range with both natural plus human-induced factors (red line with pink shading). Natural factors include volcanic and solar activity, while human-induced activity adds the effects of greenhouse gases, sulfates, and ozone (Meehl et al., 2009). In the Pacific region, high ENSO-related variability makes it more difficult to separate the long-term and short-term trends. (From Meehl et al. [2009] by permission of American Meteorological Society.)

appropriate variables as "essential climate variables" (ECV). Much of the required data covering 50 ECVs is routinely collected by observing systems. However, many key regions and climatic zones remain poorly observed, and many of these observing systems, particularly those of non-satellite based atmospheric and terrestrial networks, have been in severe decline in quality and overall scientific veracity over the past few decades (IPCC, 2007; Trenberth, 2008; Manton et al., 2010; Karl et al., 2010). This decline in monitoring networks is particularly evident in the Pacific Islands region.

Over the past few decades, satellites and other types of observing systems such as drifters and gliders (e.g., Argo profiling floats and Autonomous Underwater Vehicles, or AUVs) have revolutionized our understanding of the climate system. With respect to sea-level rise (SLR), for example, satellite altimeters along with the Gravity Recovery and Climate Experiment (GRACE) project and Argo have been providing detailed measurements of sea-surface height across the ocean surface and tracking the factors that are critical to understanding the global sea-level budget (Leuliette & Miller, 2009; Leuliette & Willis, 2011). These systems are not working alone. In the Pacific, a robust network of sea-level stations, including those in NOAA's National Water Level Observation Network (NWLON) and the larger Global Sea Level Observing System (GLOSS) Global Core Network (GCN), monitor local water levels and help to calibrate and validate the space-based observations.

Unfortunately, similar progress cannot be reported with respect to systems making in situ measurements of other important parameters such as surface temperature, precipitation, and water resources. Rather, many of these systems in the region have been in decline over the past few decades. In Hawai'i, for example, both the number of active rain gauges and the number of streamflow gauges have decreased dramatically since the 1960s (Giambelluca et al., 2011; Oki, 2004). Elsewhere in the region, the situation is worse and is exacerbated further by the lack of resources needed to support data management as well as maintain observing systems and associated infrastructure. For other observing systems and monitoring methods, decline is not the primary issue: adequate networks and protocols have never been established. For example, few long records of wave height are available for the region on the whole. Similarly, more GPS stations and longer time series are needed to better assess local land motion. The collection of ecosystem-related data, while improving, is insufficient. In addition, there is an urgent need to link physical, chemical, and biological observations with socioeconomic data as a means to better understand and predict impacts. Providing a robust observing system goes beyond addressing the needs of the region. Considering the role the Pacific plays in the global climate system along with the existence of unique and pristine ecosystems in the region, enhanced monitoring affords an opportunity to advance the overall state of knowledge and assess the impacts of climate change.

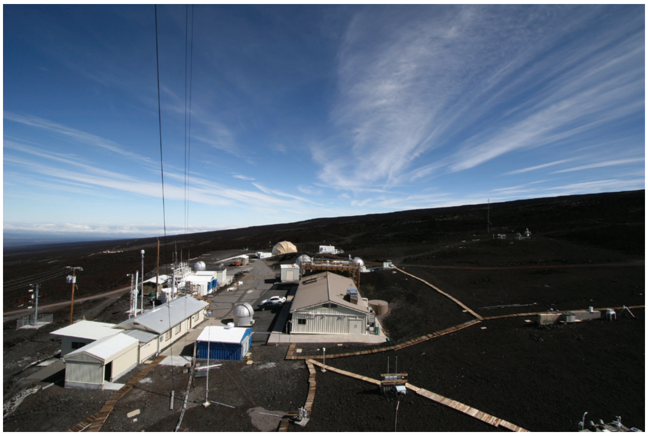
Models and projections

Global climate models (GCMs), which simulate the workings of the climate systems, provide a basis for projecting future climate change. Greenhouse gas emissions "scenarios" are used to drive model runs. Typical results reflect output from multiple runs of multiple models. For example, in the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC), 18 global modeling centers contributed outputs from hundreds of simulations coordinated through the Coupled Model Intercomparison Project Phase 3 (CMIP3). Generally recognized sources of uncertainty in GCM outputs include incomplete understanding of (a) the factors that govern climate change, chiefly the sources and sinks of human-induced factors; (b) the response of the climate system to those factors; and (c) the role of natural variability (Mote et al., 2011).

Previous assessments by the IPCC used four categorizations for their scenarios of

Box 1-4

The value of high-quality observations and monitoring: Mauna Loa Observatory, HaleNet, and Station ALOHA



Box 1-4 Photo 1 The Mauna Loa Observatory sits at an elevation of 11,141 feet above sea level on Hawai‘i Island and is the site of the longest high-quality record of atmospheric carbon dioxide, known as the Keeling Curve. Funding to maintain the station has been in jeopardy since the station started taking measurements in the mid-1950s. (© Forest M. Mims III. Used with permission.)

The longest high-quality record of atmospheric carbon dioxide (CO_2) is on Hawai‘i Island at the Mauna Loa Observatory, an atmospheric research station at an elevation of 11,141 feet above sea level. The Mauna Loa Observatory has been recording atmospheric CO_2 since the mid-1950s and is a valuable record because of the undisturbed air, minimal human influence, and remote location. The record of CO_2, also known as the Keeling Curve (after Charles Keeling), is a crucial resource for building models of global climate (Figure 1-7).

HaleNet I was established in 1988–90 and consists of two transects of climate stations along the leeward and windward slopes of Haleakalā National Park on the island of Maui, Hawaiian Islands. Spanning elevations from 3,117 to 9,843 feet, HaleNet I provides baseline data for monitoring climate variability and change as well as ecological responses. HaleNet II was established in 1992 on the windward slope of Haleakalā to document baseline conditions and response to El Niño–induced droughts from the heart of montane forest up through the treeline and trade wind inversion layer. HaleNet provides the only long-term terrestrial bioclimate monitoring data set in the Pacific Islands and is an important resource for understanding ecological responses to changing climatic conditions (see *http://climate.socialsciences.hawaii.edu/HaleNet/HaleNet.htm*).

Station ALOHA is an oceanographic research area located about 60 nautical miles north of the island of O‘ahu (University of Hawai‘i at Mānoa, 2012). For more than 20 years, monthly research cruises to Station ALOHA have yielded the most detailed record to date on ocean acidification in the Pacific. The cruises were conducted under the Hawai‘i Ocean Time-series program (HOT) established in 1988 by Dave Karl and Roger Lukas of the School of Ocean, Earth Science and Technology (SOEST) at the University of Hawai‘i at Mānoa.

Box 1-4 (Continued)

Station ALOHA currently includes a seafloor observatory, which measures salinity, temperature, and currents, as well as hydrophones and a camera for monitoring deep-sea activity.

Data from the Mauna Loa Observatory, HaleNet, and Station ALOHA have proven invaluable to science. However, maintaining these observing capabilities is a challenge. Funding for the Mauna Loa Observatory has been in jeopardy as long as it has existed. The station has mostly remained open due to the tireless efforts of small groups of passionate atmospheric scientists who put together small amounts of funding to support "routine monitoring," a category that funding agencies prefer to overlook in favor of research (Weart, 1997). Without data to support it, there can be no research. Additional ways to secure more support are needed to maintain this network of monitoring stations.

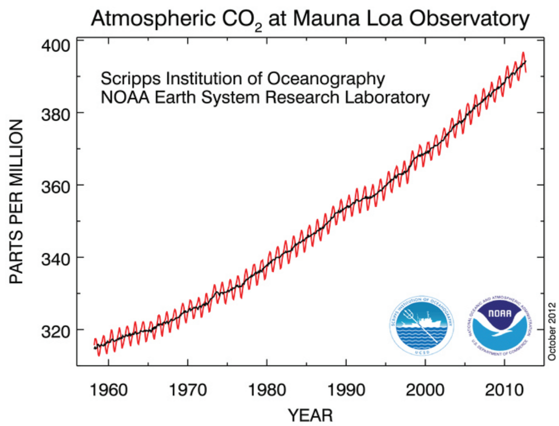


Figure 1-7 The Keeling Curve: observed atmospheric CO_2, 1958–2011. (Courtesy of Dr. Pieter Tans, NOAA ESRL, and Dr. Ralph Keeling, Scripps Institution of Oceanography.)

future emissions and climate, each with different assumptions about future population, socioeconomic conditions, and technological advances: A1, A2, B1, and B2 (Meehl et al., 2007). The A1 scenario assumes a future with very rapid economic growth, a global population that peaks mid-century, and rapid development and use of efficient technology. The B1 scenario uses the same population assumptions as A1, with more rapid socioeconomic changes, toward a service and information economy. B2 has intermediate population and economic growth while focusing on local solutions and environmental stability. The final A2 scenario has high population growth and slow economic development and technological change. Many groups of climate modelers use these scenarios to simulate a range of potential future conditions. The A2 and B1 scenarios are used in the PIRCA report.

Figure 1-8 shows CMIP3 multi-model mean annual temperature for Hawai'i in three future time periods (2035, 2055, 2085) and two emissions scenarios (A2, B1). Predicted temperatures increase steadily compared to 1971–2000, representing a continuation of the upward trend in mean temperature in the region over the past century. Temperatures are consistently higher for the A2 scenario, and there is little or no spatial variation, especially for the A2 scenario. For 2035, B1 values range from 0.56° to 1.11°C (1° to 2°F), and A2 values range from 0.83° to 1.11°C (1.5° to 2°F) higher than values for 1971–2000. For 2055, B1 values range from 0.83° to 1.39°C (1.5° to 2.5°F), and A2 values range from 1.67° to 1.94°C (3° to 3.5°F) higher. Increases by 2085 are larger still, ranging from 1.39° to 1.67°C (2.5° to 3°F) for B1 and from 2.5° to 2.78°C (4.5° to 5°F) for A2 higher than 1971–2000 values. The sign and magnitude of the trends indicated in projections are in general agreement with the trends found in historic observations (discussed in detail in Chapter 2).

Although predictions are less certain than those for mean annual temperature, the CMIP3 multi-model shown in Figure 1-8 also predicts annual rainfall for Hawai‘i for the three future years (2035, 2055, 2085) and two emissions scenarios (A2, B1), showing a general south-north gradient in changes. Despite a downward trend over the past century, by 2085 the southern parts of the state show relatively large increases while the northern areas show slight decreases. This gradient increases in magnitude as time progresses for both scenarios. The largest south-north differences are for the A2 scenario in 2085, varying from an increase of 7.5% over 1971–2000 values south of the Big Island to a decrease of 3.5% in Kaua‘i. The weakest difference occurs for the B1 scenario in 2035, with decreases of 0.5% to 2.5% below values for 1971–2000. The weakest difference occurs for the B1 scenario in 2035, with decreases of 0.5% to 2.5% below values for 1971–2000. Individual

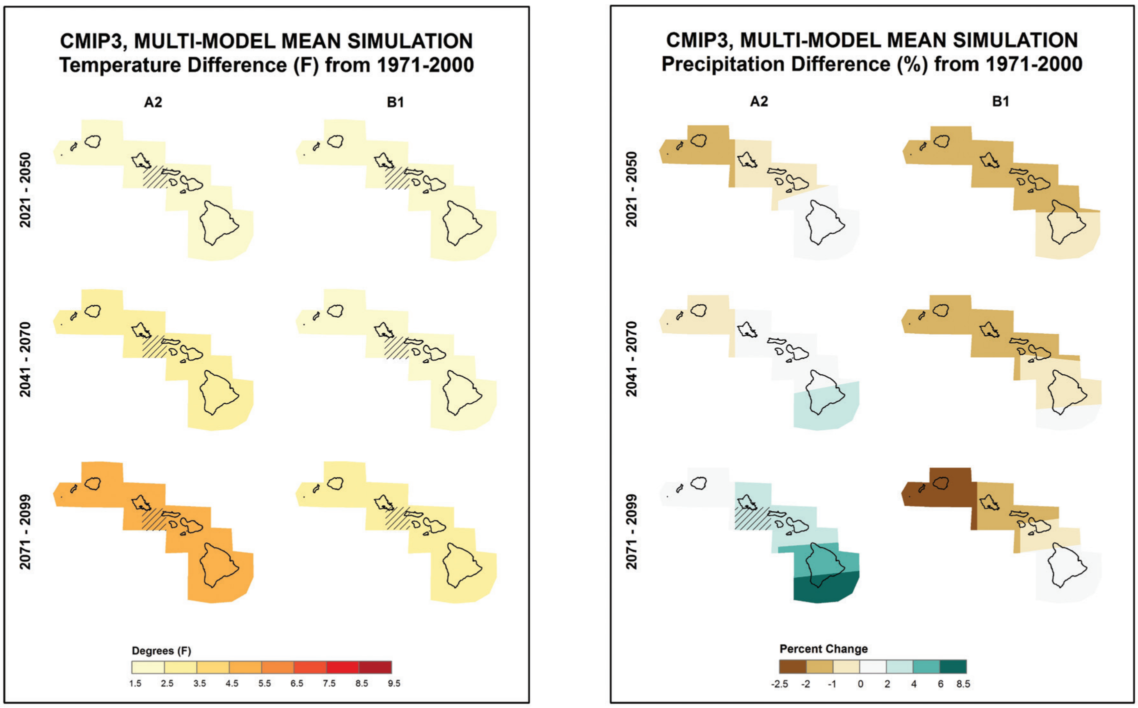


Figure 1-8 Multi-model mean annual differences in (left) temperature (°F) and (right) precipitation (%) in Hawai‘i between the three future periods and 1971–2000, from the 15 CMIP3 model simulations. (Courtesy of Ken Kunkel, NOAA NCDC and North Carolina State University.)

model realizations from the multi-model predictions of regional precipitation generally have more variability and therefore more uncertainty than those associated with temperature. However, this uncertainty can be reduced by improving regional model downscaling.

For the Central South Pacific sub-region, CMIP3 models project that annual surface air temperatures (SATs) for both B1 and A2 emissions scenarios will range from 0.61° to 0.72°C (1.1° to 1.3°F) higher than 1971–2000 values by 2030, 1.06° to 1.39°C (1.9° to 2.5°F) higher by 2055, and 1.39° to 2.67°C (2.5° to 4.8°F) higher by 2090 (Australian Bureau of Meteorology & CSIRO, 2011). Warming trends are also projected for the WNP, with annual SATs for both scenarios ranging from 0.61°C to 0.72°C (1.1° to 1.3°F) higher by 2030, 1.06° to 1.44°C (1.9° to 2.6°F) higher by 2055, and 1.5° to 2.83°C (2.7° to 5.1°F) higher by 2090 (Australian Bureau of Meteorology & CSIRO, 2011). The intensity and frequency of days of extreme heat are also projected to increase over the course of the 21st century for all regions (with very high confidence).

Although predictions of higher temperature are consistent with the historic trend, predictions of higher rainfall are not. And, as noted in Appendix B, there are also substantial differences among projections by specific models. These two findings highlight a critical area for future research. Another important consideration with respect to model projections is inadequate spatial resolution. “Regional downscaling” is needed, in particular, to address issues related to the geography and associated atmospheric dynamics of the high islands. While downscaling at higher resolutions will be beneficial for all US regions, it is crucial for Hawai‘i and the USAPI, as islands were too small to appear as landforms at the scale used for GCMs in the IPCC AR4 in 2007. Adequate spatial and temporal resolution is critical if model outputs are to be used to assess impacts and support climate adaptation planning. Appendix B discusses issues related to downscaling as well as the results of current efforts to improve spatial resolution.

Finally, natural year-to-year variability represents an additional complicating factor in determining the mean response of tropical Pacific circulation patterns to climate change (as described earlier in this chapter). The goal of developing scenarios is perhaps best viewed as helping to distinguish the slowly varying central tendency of climate change from shorter-term variations. In the region, short-term variations are important (and even dominant) when the objective is to identify and interpret climate change on small scales of time and space (Mote et al., 2011; Hawkins & Sutton, 2010; Giorgi, 2005).

Indicators of a changing climate in the Pacific Islands region

Despite the challenges of distinguishing natural variability from long-term changes, and in analyzing historic and projected trends, several key indicators reflect observed change and can serve as a basis for monitoring and evaluating future change (Figure 1-9).

- **Carbon dioxide (CO_2) concentrations are rising.** Since the start of the industrial revolution, the concentration of CO_2 in the atmosphere has increased by roughly 35 percent (NOAA NCDC, 2011). As of May 2012, CO_2 measurement from the Mauna Loa observatory was 396.78 parts per million (ppm). Over the last 800,000 years, atmospheric carbon dioxide (CO_2) concentrations have varied within a range of about 170 to 300 ppm.

- **Surface air temperature is rising.** Air temperature has increased throughout the region. In Hawai‘i, average temperatures for all stations increased by 0.08°F per decade over the period 1919 to 2006. In recent years, the rate of increase has been accelerating, particularly at high elevations (Giambelluca et al., 2008). In the WNP, observed maximum and minimum temperatures increased over the past 60 years (Kruk et al., 2012; Lander & Guard, 2003; Lander & Khosrowpanah, 2004; Lander, 2004). In the CSP, there has been a general warming trend in average, minimum, and maximum temperatures since the 1950s (Australian Bureau of Meteorology & CSIRO, 2011). Annual surface air temperatures are projected to increase for the entire Pacific Islands region under A2 and B1 emissions scenarios (Australian Bureau of Meteorology & CSIRO, 2011).

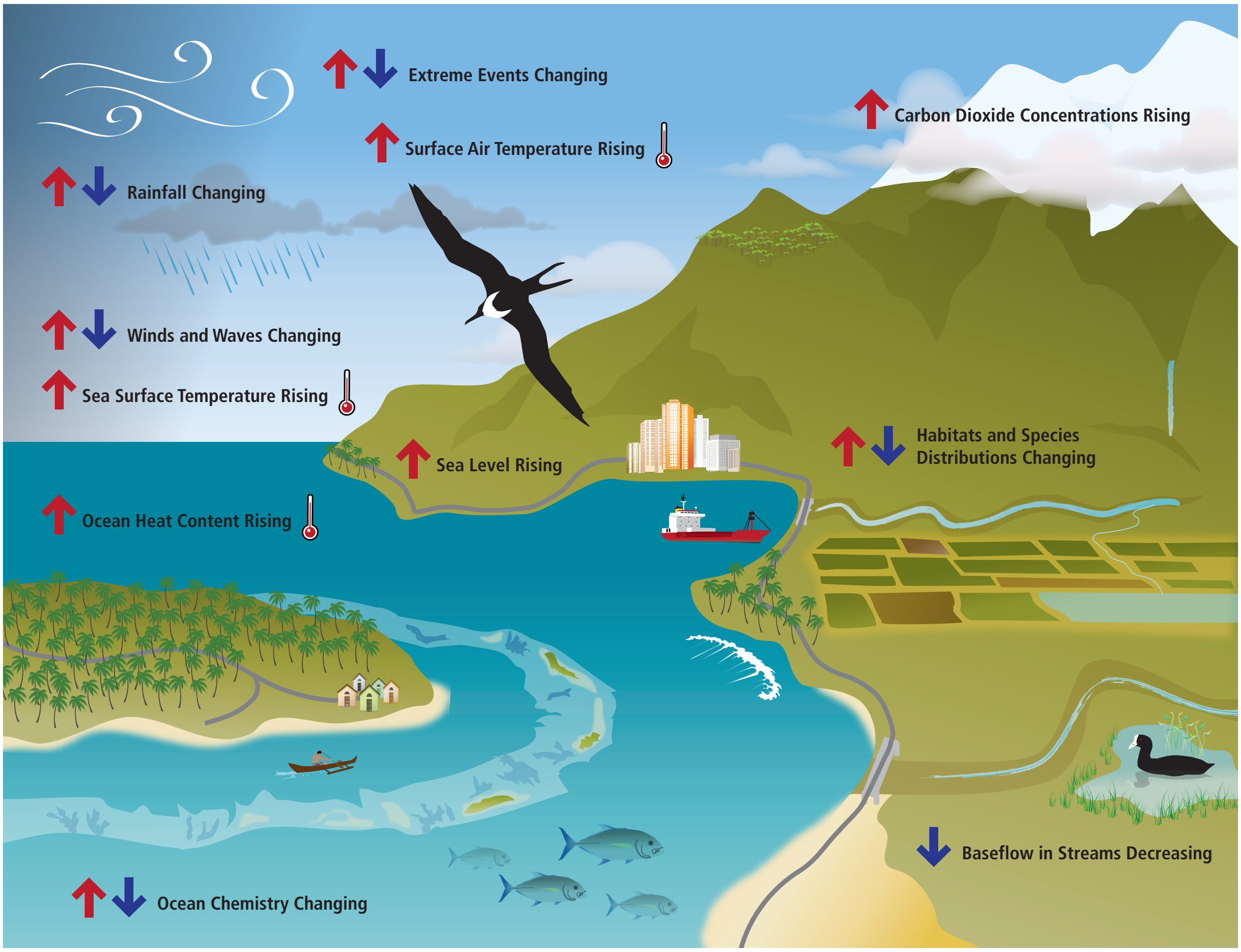


Figure 1-9 Indicators of climate change in the Pacific Islands region. (Courtesy of Susan Yamamoto, Geovision. Adapted from "Ten Indicators of a Warming World," in NOAA National Climatic Data Center, State of the Climate 2009 [report].)

- **Sea level is rising.** Global mean sea level has been rising at an average rate of approximately 0.13 inches +/-0.02 inches (3.4 mm +/- 0.4 mm) per year since the early 1990s (Nerem et al., 2010). This rate, based on satellite altimeter measurements, is twice the estimated rate for the 20th century based on tide-gauge measurements (Church & White, 2006; Bindoff et al., 2007). Rates of sea-level rise in the region during the altimetry period exceed the global rate, with the highest increases occurring in the WNP (Cazenave & Llovel, 2010; Nerem et al., 2010; Timmermann et al., 2010). Regional changes exceeding the global average are attributed to changes in wind, as well as natural climate variability (Di Lorenzo et al., 2010; Bromirski et al., 2011; Merrifield, 2011). Globally, much of the SLR to date is a result of thermal expansion associated with ocean warming. The global rate is expected to increase as melting land ice (e.g., from Greenland and mountain glaciers) adds water to the ocean.
- **Sea-surface temperature is rising.** Since the 1970s, sea-surface temperature (SST) has increased at a rate of 0.13° to 0.41°F (0.07° to 0.23°C) per decade, depending on the location. Projected increases in SST for the Pacific Islands region range from 1.1° to 1.3°F by 2030, 1.6° to 2.5°F by 2055, and 2.3° to 4.9°F by 2090 under B1 and A2 emission scenarios (Australian Bureau of Meteorology & CSIRO, 2011).
- **Upper-ocean heat content is rising (stratification is changing).** While ocean heat content varies significantly across time and place due to changing ocean currents and natural variability, there has been a strong warming trend in recent decades (NOAA NCDC, 2011). Model projections show a 30% expansion of subtropical areas by 2100, whereas temperate and equatorial areas decrease by 34% and 28%, respectively (Polovina et al., 2011). This is due primarily to enhanced stratification and a northward shift in the prevailing mid-latitude winds blowing from the west.
- **Ocean chemistry is changing.** When human-induced carbon dioxide is absorbed by seawater, chemical reactions occur that reduce saturation states of the minerals calcite and aragonite (a process referred to as ocean acidification). Surface pH has dropped by 0.1 pH units and is projected to decline an additional 0.2 to 0.3 pH units by 2011 (Doney et al., 2012; Feely et al., 2009). Aragonite is critical to reef-building coral, and annual maximum saturation state is projected to drop below 3.5 by 2035 to 2060 around the Pacific with continuing decline thereafter (Australian Bureau of Meteorology & CSIRO, 2011).
- **Rainfall amount and distribution are changing.** Over the past century, rainfall has decreased throughout Hawaiʻi (Oki, 2004; Chu & Chen, 2005; Diaz et al., 2005, 2011; Giambelluca et al., 2011; Elison Timm et al., 2011). From 1954 to 2011, rainfall also decreased in eastern Micronesian islands such as Majuro and Kwajalein. In contrast, rainfall has increased slightly in western Micronesian islands (Bailey & Jenson, 2011; Jacklick et al., 2011). In the CSP, long-term precipitation records show no visible or significant trend (Young, 2007). Statistical downscaling by Elison Timm and Diaz (2009) projected the most

likely precipitation scenario for Hawai'i for the 21st century to be a 5% to 10% reduction for the wet season and a 5% increase in the dry season.

- **Stream base flow is decreasing.** Eight of the nine long-term stream gauges in Hawai'i show statistically significant decreases in base flow, the groundwater component of streamflow, from 1913 to 2008 (Oki, 2004; Bassiouni & Oki, 2012).
- **Winds and waves are changing**. In the WNP, the strength of the trade winds has increased since the early 1990s; correspondingly, sea level has risen (Merrifield, 2011; Merrifield & Maltrud, 2011). Observations from wave buoys suggest that wave heights have increased in the North Pacific over the past century (Ruggiero et al., 2010; Seneviratne et al., 2012).
- **Extremes are changing (e.g., drought, rainfall, coastal inundation**). Throughout Hawai'i, there is a trend toward fewer extreme rainfall events (exceeding 10 inches in 24 hours) and a propensity toward longer dry periods (Chu et al., 2010). The annual number of maximum consecutive dry days occurring during the 1980–2011 time period increased compared to years 1950–1970 (Chu et al., 2010). Since the 1950s, there have been fewer extreme rainfall events (exceeding 10 inches in 24 hours) in Guam and the CNMI (Lander & Guard, 2003; Lander & Khosrowpanah, 2004). The WNP basin (the world's most prolific typhoon basin) has been very calm in recent years (Knapp et al., 2010; Maue, 2011). The CNP also appears to be experiencing fewer tropical cyclones (Chu, 2002). In contrast, tide-gauge observations at Midway Atoll, in the Hawaiian archipelago, suggest that the number of storm wave events originating from outside the tropics has increased significantly over the past 50 years (Aucan et al., 2012).
- **Habitats (and species distributions) are changing.** Significant, widespread ecosystem changes have occurred in the Pacific Islands region, and continued change is highly likely. Many coral reefs are endangered and perhaps dying due to the cumulative effects of fishing practices, land-based sources of pollution, sedimentation, physical damage from anchors and vessels, coastal development, invasive species, and changes in ocean temperature and chemistry. Changes in distribution of open-ocean fish species are associated with changes in ocean temperatures (Polovina et al., 2011). Coastal wetlands and mangrove areas are becoming more saline over time, with increased inundation from high waves, and Pacific Island mangroves may be substantially reduced by 2100 (Gilman et al., 2008). Projections of temperature and rainfall suggest that by 2100, climate change will have created new, coastal low-elevation growth conditions in areas that are already dominated by invasive species. At higher elevations, some wet native ecosystems will no longer exist by 2100.

Impacts of a changing climate in the Pacific Islands region

Decision makers in all sectors are faced with addressing the impacts of the changing climate in the Pacific Islands region. Key climate-related vulnerabilities facing the region's natural resources and the communities that rely upon those resources are summarized below.

Low islands, coral reefs, nearshore and coastal areas on high islands, and high-elevation ecosystems (particularly alpine and subalpine) are most vulnerable to climatic changes. In marine ecosystems, large-scale changes in wind regimes, thermal stratification, and ocean chemistry affect phytoplankton distribution (Polovina et al., 2008), which, in turn, will likely change the distribution of species all along the food chain. Species dependent on fixed islands for breeding, however, such as seabirds, may not be able to adapt to these changing conditions (Frederiksen et al., 2004). Rates of coral reef formation are declining, presumably due to ocean acidification (Cooper et al., 2008), and coral bleaching due to extreme sea-surface temperatures is becoming more frequent and widespread (Veron et al., 2009). Seagrass and mangrove ecosystems, which serve as foraging areas and nursery habitat for many coastal species, are expected to diminish due to the combined effects of increased air and sea temperature, sea-level rise, drought, and increased runoff and sedimentation (Waycott et al., 2011).

Coastal and atoll island ecosystems will be affected by high waves during storms, which will reshape and move islets and beaches and increase salinity. These changes will reduce or eliminate endemic terrestrial species, seabird colonies, sea turtle nests, and human presence on many small islands. Freshwater ecosystems face a gradual decline of native aquatic species as rainfall and streamflow decline. Invasive species of plants and animals are established and expanding in many island forests, and their response to climate change will interact with those of native species to determine the composition of future ecosystems. Existing climate zones are projected to shift, generally upslope, with some eventually disappearing (Benning et al., 2002). Because many island species are endemic, the loss of a species from an island ecosystem often means global extinction.

Warmer and drier conditions mean that freshwater supplies will become more limited on many Pacific Islands. Low islands are especially vulnerable to freshwater shortages due to their small size and limited resources. Food security will be affected if prolonged drought threatens crop productivity or if storms damage infrastructure such as crop and

Photo 1-1 The coastal ecosystems of the Pacific Islands region serve as a nesting ground for populations of endangered green sea turtles. (Courtesy of Andy Bruckner, NOAA.)

water storage facilities, irrigation systems, roadways, or equipment. In addition, sea-level rise will decrease the land area available for farming (Easterling et al., 2007) and may increase the salinity of groundwater resources (Carter et al., 2001).

Photo 1-2 Nukuoro Atoll is part of the Federated States of Micronesia. Its lagoon is about 3.7 miles in diameter, and it has an approximate land area of 0.7 square miles. (Courtesy of NASA.)

In general, the proximity of human settlements and major infrastructure to the ocean increases the vulnerability of all Pacific Islands. Almost without exception, international airports are sited on or within one to two miles of the coast, and the main (and often only) road network runs along the coastline (Walker & Barrie, 2006). Because Pacific Islands are almost entirely dependent on imported food, fuel, and material (Austin et al., 2011), the vulnerability of ports and airports to incremental increases in sea level and to extreme events, especially tropical cyclones, is of great concern.

The economic impact of climate change is expected to be substantial because island economies generally depend on limited sources of revenue and are thus particularly exposed to external shocks. In the 1990s alone, tropical cyclones cost the region more than $1 billion, a figure that will increase if more intensified storms occur in the future (Mendelsohn et al., 2012). Damages to transportation infrastructure from storms or SLR, along with probable increases in fuel costs, will increase stress on island economies. In the fisheries sector, one ecosystem model coupled with a climate model indicates that by 2100 under the A2 scenario, the catch for both skipjack and bigeye tuna will decline overall by 8% and 27%, respectively, but with important spatial differences. The western Pacific is projected to show the greatest declines in both fisheries, whereas the eastern Pacific is projected to show an increase for skipjack and a decline for bigeye (Lehodey et al., 2011). Pacific Island tourism risks losing billions of dollars annually if SLR or storms threaten infrastructure, ocean bleaching threatens the recreational appeal of coral reefs, or freshwater supplies decrease.

Climate change may also have serious effects on human health, for instance by increasing the incidence of infectious diseases such as dengue (Lewis, 2012). Sea-level rise and flooding may also overcome sewer systems and threaten public sanitation. Psychosocial effects of stress from extreme weather events are likely to be gradual and cumulative. Increased incidences of resource conflicts may also affect mental and physical health, with a disproportionate impact on those of lower socioeconomic status (Swim et al., 2010).

Ultimately, the changing climate poses serious consequences to the traditional lifestyles and cultures of indigenous communities in all Pacific Island sub-regions. Inundation from SLR may destroy coastal artifacts and structures (Vitousek et al., 2004) or even the entire land base associated with cultural traditions (Henry & Jeffery, 2008). Drought threatens traditional food sources such as taro and breadfruit, and coral mortality from bleaching will likely threaten subsistence fisheries in island communities (Maclellan, 2009). Climate-related environmental deterioration for communities at or near the coast, coupled with other socioeconomic or political motivations, may lead individuals, families, or communities to consider migrating to a new location. Depending on the scale and distance of the migration, a variety of challenges faces the migrants and the communities receiving them. Migrants need to establish themselves in their new community, find employment, and access services, while the receiving community's infrastructure, labor market, commerce, natural resources, and governance structures need to absorb a sudden burst of population growth. In addition, loss of local and traditional knowledge associated with stresses to ecosystems may limit the effectiveness of adaptation (Adger et al., 2007; Burkett, 2011).

Adaptive capacities

Within the region, adaptive capacity differs with the availability of socioeconomic and institutional resources. The difference tends to reflect the high island/low island distinction because high islands can better support larger populations and infrastructure, which in turn attracts industry and allows the growth of different types of institutions. The level of executive leadership (from both governmental and non-government institutions) currently focusing on climate issues varies by jurisdiction and sector. In the public sector, the current administrations of Hawai'i and American Sāmoa are taking action at several levels to address the impact of climate change. For example, as part of his "New Day" plan for the state, Hawai'i governor Neil Abercrombie recently stated that "the time for a long-term plan for the effects of climate change is now" (New Day Hawai'i, 2010). In 2012, the Hawai'i State Legislature passed a law (SB 2745) that amends the State Planning Act by adding climate change as one of ten statewide priority guidelines and provides specific guidance on how to do this, including "encourage planning and management of the natural and built environments to effectively integrate climate change policy." Impacts of sea-level rise are incorporated in plans developed by the City and County of Honolulu Board of Water Supply for managing the Ko'olau Loa and Wai'anae watersheds (Group 70 International, 2009; Townscape, Inc., 2009). Climate scenarios have also played a role in ongoing planning for project design in Micronesia, where a coastal highway was designed with consideration of sea-level risk impacts (Adger et al., 2007). In American Sāmoa, Governor Togiola Tulafono has long supported action to prepare for the effects of climate change on coral reefs. Following his administration's addition of climate vulnerability as a territorial priority in 2011, Tulafono mandated the establishment of the Climate Change Adaptation Advisory Group (Sagapolutele, 2011).

Box 1-5

Climate change will force human migration from the Pacific Islands

When violent conflicts force residents of a country to abandon their homes, families, or property, there are international instruments, such as the Geneva Convention of 1951, that provide refugees with rights and define the legal obligations of host states. Although the Intergovernmental Panel on Climate Change (IPCC) first identified climate-induced human migration as a grave issue in their First Assessment in 1990 (Tegart et al., 1990), there is still no single legal entity that governs climate-induced migration, nor has there been significant legal or political progress in addressing this phenomenon.

Even the appropriate terminology remains undefined. Since the term “refugee” confers a certain set of legal rights reserved for circumstances involving immediate conflict or persecution, legal scholars and academics frequently use the term “climate migrants” (Burkett, 2011). Projections of the number of climate migrants by 2050 range from 25 million to 1 billion (International Organization for Migration, 2009). This large range demonstrates both the potential magnitude of the problem and the lack of appropriate data on which to base estimates. The Pacific Islands region is currently facing an immense and unprecedented loss of homeland in its thousands of low-lying islands and atolls. Unlike other populations facing climate-induced migration, Pacific Islanders from countries such as the Republic of the Marshall Islands will not be able to migrate domestically because their entire country is only a few feet above sea level.

These climate migrants may permanently lose the entirety of their homeland, leaving it unclear under current international law if they will retain an array of legal benefits and other economic rights to the area of ocean their country once inhabited. Although Pacific Island nations are the first to suffer the large-scale consequences of climate change, their contribution to greenhouse gas emissions has been minimal. While the issue of climate-induced migration is recognized globally, the complexity in the associated international governance policies has so far prevented any one organization or government from taking a leadership role. There must be a concerted global effort to resolve the current and future migration issues of Pacific Islanders as soon as possible, before the problem becomes insurmountable.

Box 1-5 Photo 1 Namdrik Atoll, in the Republic of the Marshall Islands, has a land area of 1.1 square miles and a maximum elevation of 10 feet. Namdrik and other Pacific Islands like it are among the first places that will face the possibility of climate-induced human migration. (Courtesy of Darren Nakata.)

Another opportunity to improve adaptive capacity is through hazard mitigation planning. Jurisdictions with current mitigation plans (see Table 1-2) are eligible for funding and resources from the US Federal Emergency Management Agency (FEMA). FEMA does not explicitly list climate change as one of the hazards that should be considered, but proposed mitigation actions are often the same for climate adaptation and climate-related hazards. Both Hawaiʻi and American Sāmoa specifically consider climate variability and change in their plans, and CNMI lists climate variability as a possible hazard related to extreme climate events (Anderson, 2012a). Currently, the US Pacific Island Freely Associated States (RMI, FSM, RP) are not eligible for funding from FEMA but have worked with regional organizations to develop plans and access international resources. They participate in the international disaster risk reduction framework, the Hyogo Framework of Action, which focuses on the risk of impacts from climate-related disasters. There are currently opportunities to integrate national action plans for disaster risk reduction and climate change adaption through the initiation of the Joint National Action Plans for Disaster Risk Management. RMI, FSM, and the RP have each developed a status report on integrating climate-related hazard information in disaster risk reduction planning and have developed plans for adaptation to climate-related disaster risks (Anderson, 2012b).

Table 1-2: Existing hazard mitigation plans in Hawaiʻi and the US-Affiliated Pacific Islands

Location	**Plan Type**	**Year Created/ Updated**
American Sāmoa	American Sāmoa Revision and Update of the Territory Hazard Mitigation Plan	2008
Commonwealth of the Northern Mariana Islands	Commonwealth of the Northern Mariana Islands Standard State Mitigation Plan	2010
Guam	2008 Guam Hazard Mitigation Plan	2008
State of Hawaiʻi	State of Hawaiʻi Multi-Hazard Mitigation Plan, 2010 Update	2010 (Update)
County of Hawaiʻi	County of Hawaiʻi Multi-Hazard Mitigation Plan	2010
County of Kauaʻi	Kauaʻi County Multi-Hazard Mitigation Plan, 2009 Update	2009
County of Maui	Maui County Multi-Hazard Mitigation Plan, 2010, Volumes I and II	2010
County of Honolulu	Multi-Hazard Pre-Disaster Mitigation Plan for the City & County of Honolulu, Volumes I and II	2010

One major gap in existing hazard mitigation plans is the inclusion of climate change impacts in modeling hazard risk and vulnerability. Models and assessment tools provide some information (e.g., erosion rates) about impacts resulting from natural hazards, but many data sets are too short-term to understand trends and probabilities of occurrence with climate change (Anderson, 2012a). Impacts resulting from severe weather coupled with climate change impacts, such as SLR and coastal inundation, are likely to exacerbate the effects of natural hazards. Another gap relates to estimating losses from climate-related hazards. Economic and social losses from climate-related hazards are generally under-reported. Since projected losses primarily rely on historical records, projections for climate change damages need to be improved to more accurately predict impacts on assets such as infrastructures (Anderson, 2012c).

Advancing knowledge

To better understand climate change and its impacts in the Pacific Islands region, knowledge needs to advance in several key areas. First, research is needed to understand historical, current, and future climate trends. Robust data on temperature, rainfall, streamflow, winds, waves, and other variables are needed to understand historic changes in physical and natural systems and to verify models of projected change. The current lack of funding for monitoring or for developing more complete climate observation networks across this vast region is of critical concern. Downscaling of global climate models is also needed to account for regional and local phenomena. Higher-resolution models can begin to simulate local conditions and generate new capacity for planning adaptation measures. An important component of this research will be analyses of the uncertainties inherent in the next generation of models. Better quantifications of and reductions in uncertainty may come from a better understanding of natural variation at inter-annual and interdecadal scales.

In addition, integrated biogeochemical and physical models need to be developed and tested to provide a better understanding of the biological and ecological responses to climate change. For instance, understanding how invasive species will react to climate change is important for developing effective plans to manage natural resources. Understanding the impact of changing carbonate chemistry in the ocean is needed to understand and prepare for changes in coral reefs and key marine organisms. Similarly, socio-ecological models need to reflect the dynamic interactions between human communities and the ecosystems they rely on and how these relationships are altered under different climate scenarios.

Finally, research examining the role of climate science in Pacific Island communities' responses to climate change will help to identify barriers to the use of climate information by public and private decision makers. Such research will also facilitate development of visualization tools and decision support systems that address real-world problems. The effectiveness of alternative adaptation strategies needs to be evaluated comprehensively to refine planning and management strategies.

Partnerships are fundamental for sustaining a regional climate assessment process and addressing the impacts of climate change across isolated and diverse islands. Key partners include stakeholders who make real-world decisions (e.g., water managers, farmers, conservationists, hazards managers, urban planners, tourism developers, cultural leaders) because they can help to identify the most urgent problems and needed information. Regional networks are also key in facilitating communication, coordinating and leveraging resources, and efficiently linking stakeholders, scientists, and institutions to develop actionable information and decision support tools. Although the jurisdictions in the region can make considerable progress with their own policies and resources, the scale of vulnerabilities and impacts suggests a strong role also for the federal government.

Conclusion

Climate change poses enormous challenges to the Pacific Islands and their communities. An informed and timely response is necessary to enhance resilience to the myriad changes already occurring and those yet to come. Local action to reduce existing stress on island people and ecosystems is a critical part of enhancing resilience. Additional research, continued monitoring, a sustained assessment process, and public engagement in the development of useful information will enhance Pacific Islanders' ability to address the climate challenges they confront. The current regional professional culture of communication and collaboration, with roots in indigenous island cultures, provides a strong foundation for this effort and will be important for building resilience in the face of the changing climate.

Box 1-6

Assessing information needs for managing O'ahu's freshwater resources

To make sure that we will have water for our homes, our farms, and our businesses in the future, planners and policymakers need good information that helps them predict both our water use and the likely state of our water resources. This is true on the Hawaiian island of O'ahu and many other Pacific Islands. Yet, many agencies responsible for formulating and evaluating plans for freshwater use do not feel that they have the information and guidance they need (PaCIS Research and Assessment Working Group, 2008), particularly on the complex issue of climate variability and change.

What are the forecasts for Hawai'i's resident and visitor populations in the coming years? How will our economy change and develop? How has the decline of the sugar industry affected water availability? Will our climate be hotter or cooler, wetter or drier? And how will climate conditions affect the amount and quality of the water available in our Pearl Harbor aquifer, which serves most of the 953,207 people who live on O'ahu, the 7.2 million tourists who visit every year, and the military bases critical for national defense?

Most local experts agree that the water use allowed on O'ahu by existing permits is close to the aquifer's maximum sustainable yield (Wilson Okamoto Corporation, 2008). Yet, demand for water is expected to increase with population growth and economic development. Where will the additional water come from? Greater water use will, in the long term, result in a decline in water levels, increasing the risk of saltwater intrusion and reducing the natural groundwater discharge to

Box 1-6 (Continued)

streams and the ocean. How much the water level declines depends on several factors, including the distribution and rate of water use, the hydraulic characteristics of the aquifer system, and the future state of the climate.

The need for climate information

In 2011, the Pacific RISA research team surveyed planners and policymakers responsible for managing our freshwater resources, through both face-to-face meetings and an online questionnaire. The goal was to gain a better understanding of their information needs. The decision makers interviewed came from a diverse range of federal, state, and local government agencies, non-government organizations, private enterprises, and local community groups. They represented a range of occupations, including project or resource managers, engineers, planners, and agency directors. Overall, they were well-informed about climate, but they reported problems with accessing climate information and using that information for planning and policymaking.

Three types of information and analysis will provide the basis for good planning decisions about freshwater use on O'ahu—(1) predictions of economic development and population growth, (2) assessments of community preferences and needs, and (3) forecasts of climate change and variability. During the recent interviews, local planners and policymakers listed several questions they face as they work to ensure good water management in light of climate change:

- What freshwater resources will be available in the long term (amount, when, for how long, where)?
- What well distributions and pumping rates are best for drier conditions in the future?
- How can water managers prevent saltwater intrusion into the supply of fresh drinking water?
- What in-stream flow standards will maintain or improve the critical habitat for endangered species?
- What alternative water sources will be needed in 50 years (e.g., desalination)?
- What alternative energy sources will be best under future climate conditions?
- How can we prevent disruption to the water supply used to irrigate crops?
- How will sustainable yield estimates be affected by projected demand for water across all sectors (e.g., agriculture, industry, energy, tourism, military) under alternative climate scenarios?
- How should county development and watershed management plans be revised to take into account projected changes in rainfall, temperature, and other climate variables in the context of the needs of a growing population?

Decision makers need climate projections that are "downscaled" from the global or regional to the local (valley) level. They also need an assessment of the inevitable uncertainties that accompany any climate projections. In general, policymakers and planners say they want information about both most-probable and worst-case scenarios. Analysis should distinguish between the effects of natural/cyclical variability, such as the El Niño-Southern Oscillation, or ENSO, and long-term climate change. Seasonal observations of precipitation, temperature, streamflow, soil moisture, and evapotranspiration are helpful for understanding current conditions. Also helpful would be location-specific vulnerability assessments and information about the implications of climate change for runoff, pollutant loads, salinity, and water supply. Decision makers emphasized that maintaining rain and stream gauges for monitoring and surveillance systems is integral and essential to providing the information needed to support decisions.

Box 1-6 (Continued)

The need for better integration of climate information in the planning process

Planners and decision makers on O'ahu mentioned several constraints that prevent them from using the climate information that is available. These include:

- No clear legal mandate requiring the use of climate information
- Insufficient staff time to locate relevant information
- A lack of expertise in knowing how to use the information
- A lack of technical assistance from the government to help access the information

The most trusted sources of information mentioned are the United States Geological Survey (USGS), the National Oceanic and Atmospheric Administration (NOAA), the University of Hawai'i, the state climatologist, and scientific journals. One priority will be to facilitate better collaboration between decision makers and these information sources.

In addition to information about climate and other factors, decisions about future water use require a balancing act between multiple users who may have divergent values. What is the right balance between protecting cultural practices and reducing energy costs, for example? What are the predicted needs of specific communities, such as kalo farmers, and economic sectors, such as tourism? Such questions can only be answered through open policy debates and decision processes within the local community.

Climate scientists and risk assessors can provide cutting-edge information about vulnerabilities and opportunities related to climate. The goal, however, is to integrate this cutting-edge information into decision making at the local level. Such an integrated approach will provide the best possible setting for making good decisions about O'ahu's water resources and water use.

Acknowledgments

Support for this research was provided by NOAA Climate Programs Office for the Pacific RISA program (Grant #NA10OAR4310216). We are grateful to the people who participated in the interviews, workshops, and survey, donating their valuable time to provide diverse and informative perspectives.

Box 1-6 Photo 1 Participants gathered at the East-West Center for the workshop "Climate Change Impacts on Freshwater Resources in Hawai'i." Participants included Barry Usagawa (left), program administrator, Water Resources, Honolulu Board of Water Supply; and Gary Gill (right), deputy director of the Department of Health's Environmental Planning Office. (Courtesy of East-West Center.)

Chapter 2

Freshwater and Drought on Pacific Islands

COORDINATING LEAD AUTHORS

Victoria W. Keener (East-West Center, Pacific RISA), Scot K. Izuka (USGS PIWSC), Stephen Anthony (USGS PIWSC)

CASE STUDY CONTRIBUTORS*

Stephen Anthony (USGS PIWSC), Victoria W. Keener (East-West Center, Pacific RISA), Jonathan L. Scheuer (Consultant), Richard Wallsgrove (ICAP, University of Hawaiʻi at Mānoa)

CONTRIBUTORS*

Hanna Annamalai (IPRC, University of Hawaiʻi at Mānoa), Ryan Bailey (Colorado State University), Tim Brown (WRCC, DRI), Jeff Burgett (PICCC), Yi-Leng Chen (Department of Meteorology, University of Hawaiʻi at Mānoa), Pao-Shin Chu (University of Hawaiʻi at Mānoa), Kati Corlew (East-West Center, Pacific RISA), Paula Cutillo (NPS), Henry F. Diaz (CIRES, University of Colorado-Boulder), Aly El-Kadi (WRRC, University of Hawaiʻi at Mānoa), Oliver Elison Timm (IPRC, University of Hawaiʻi at Mānoa), Stanton Enomoto (PICCC), Melissa L. Finucane (East-West Center, Pacific RISA), Charles Fletcher (SOEST, University of Hawaiʻi at Mānoa), Lucas Fortini (PICCC), Abby Frazier (University of Hawaiʻi at Mānoa), Thomas Giambelluca (University of Hawaiʻi at Mānoa), Kevin Hamilton (IPRC, University of Hawaiʻi at Mānoa), John Jenson (University of Guam, WERI), Kevin Kodama (Honolulu WFO), Dawn Kotowicz (NOAA), Michael Kruk (NOAA), Kenneth E. Kunkel (NOAA NCDC, North Carolina State University), Mark Lander (University of Guam, WERI), Chester Lao (Honolulu Board of Water Supply, retired), Nancy Lewis (East-West Center), Alan Mair (WRRC, University of Hawaiʻi at Mānoa), John J. Marra (NOAA NCDC), Lisa D. Miller (USGS PIWSC), Rachel L. Miller (East-West Center, Pacific RISA), Delwyn Oki (USGS PIWSC), Margaret H. Smith (East-West Center), Deanna Spooner (PICCC), Mark Stege (Asian Development Bank), Adam Stein (NOAA PSC), Sharla Stevenson (NPS, Colorado State University), William V. Sweet (NOAA COOPS)

*LISTED IN ALPHABETICAL ORDER

Freshwater resources are essential not only for human consumption but also for the agricultural, industrial, and economic health of the Pacific Islands region. Freshwater on the Pacific Islands includes groundwater, surface water, and rainwater catchment, but because islands are small and surrounded by oceans, these resources are limited. Alternatives such as desalination plants are non-existent or currently infeasible on a large scale. Generally, the smaller the island, the smaller and more vulnerable are its water resources. Maintaining an adequate freshwater supply in the Pacific Island environments is of critical concern as climate change places stresses of uncertain magnitude on already fragile resources. To ensure that Pacific Island communities maintain plentiful freshwater supplies during uncertain future climate conditions, it is necessary to understand and integrate historical trends, current conditions, and projections of future hydrological variables in the three sub-regions. The theme of this chapter focuses on historical trends in regional freshwater resources.

On larger islands, such as those in Hawai'i, American Sāmoa, and Guam, groundwater is the primary source of drinking water. It is susceptible to changes in precipitation and sea level and is affected by changes in evapotranspiration (water moving into the atmosphere through evaporation and plant transpiration). Groundwater is also vulnerable to over-pumping, contamination, and saltwater intrusion. The availability of surface water, which is used for agriculture and to supplement drinking water, is also sensitive to changes in precipitation, evapotranspiration, and changes in land cover. On smaller islands, such as the tiny low-lying islands of atolls, groundwater and surface-water resources are extremely limited and the populations must rely on a combination of rainwater catchment and groundwater for most of their drinking water. Freshwater wetlands are also the primary environment in which taro is grown, a food staple on many low islands. At only a few feet above sea level, low islands are also more vulnerable to sea-level rise, wave over-wash, and saltwater intrusion.

Freshwater hydrology overview

Most islands in the Pacific Islands region can be categorized as either "high islands," which can have peak altitudes as high as 14,000 feet above sea level, or "low islands," most of which are no more than a few tens of feet above sea level. Height above sea level affects an island's interaction with the surrounding ocean and atmosphere and ultimately determines the nature and reliability of the island's water resources. Precipitation is the source of all freshwater on the Pacific Islands. Precipitation that falls on the land can run off the surface into the ocean via streams, return to the atmosphere through evapotranspiration, or recharge groundwater (Figure 2-1). Among oceanic islands, fresh groundwater forms a lens-shaped body that overlies denser saltwater from the ocean;

This Chapter should be cited as:
Keener, V. W., Izuka, S. K., & Anthony, S. (2012). Freshwater and Drought on Pacific Islands. In V. W. Keener, J. J. Marra, M. L. Finucane, D. Spooner, & M. H. Smith (Eds.), *Climate Change and Pacific Islands: Indicators and Impacts*. Report for the 2012 Pacific Islands Regional Climate Assessment (PIRCA). Washington, DC: Island Press.

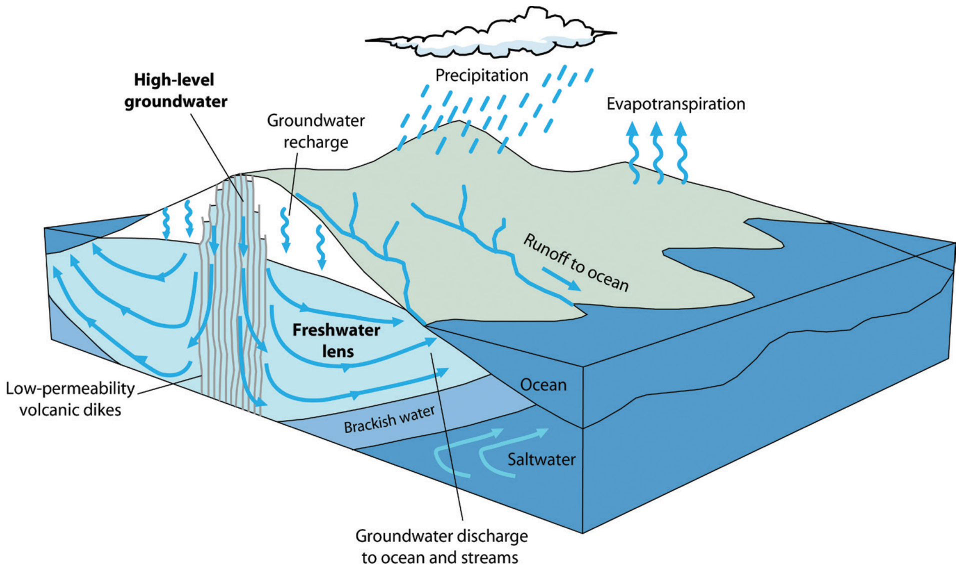


Figure 2-1 Cross section of regional hydrological processes. Precipitation is the source of both surface water, such as streams, and groundwater on Pacific Islands. Variations in precipitation and evapotranspiration rates therefore affect both resources. Surface water is important for human use and provides habitats for fragile ecosystems. Groundwater in islands exists as a freshwater lens underlain by saltwater, and on high volcanic islands it may also exist as high-level groundwater. Groundwater is a principal source of drinking water on high islands. (Modified from Izuka, 2011.)

between the freshwater lens and the underlying saltwater is a brackish transition zone. Fresh groundwater can also occur on high volcanic islands as high-level groundwater impounded by low-permeability geologic structures, such as volcanic dikes, ash layers, and massive lava flows (Hunt, 1996).

Groundwater naturally flows toward the coast, where it discharges from lowland springs, streams, and submarine seeps (Figure 2-1). On average, the amount of groundwater recharge is balanced by groundwater discharge, but droughts or unusually wet periods can result in short-term imbalances that cause the freshwater lens to shrink or grow. Climate variation and change thus affect not only surface-water resources, such as streams and lakes, but also groundwater resources.

High islands

On high islands, rainfall is enhanced by the orographic effect. Winds carrying warm, moisture-laden air from the ocean are driven upward as they encounter the island's mountains. The rising air is cooled and the condensing moisture causes rain and cloud formation (Figure 2-2). As a result of the orographic effect, rainfall on some high islands can be much higher than that of the surrounding ocean. The amount of rain can vary dramatically across the landscapes of high islands, with much higher rainfall on windward-facing mountain slopes than on leeward lowlands. On the highest mountains in Hawai'i, air reaches the trade wind inversion (TWI) layer, within which air is warmer above than below, an arrangement that effectively halts rising air and cloud development (Nullet & Giambelluca, 1990; Cao et al., 2007) (Figure 2-2). Rainfall is scant above the TWI level. Other forms of precipitation on high islands include fog drip in middle-elevation slopes, and snow, hail, and freezing rain on the highest peaks.

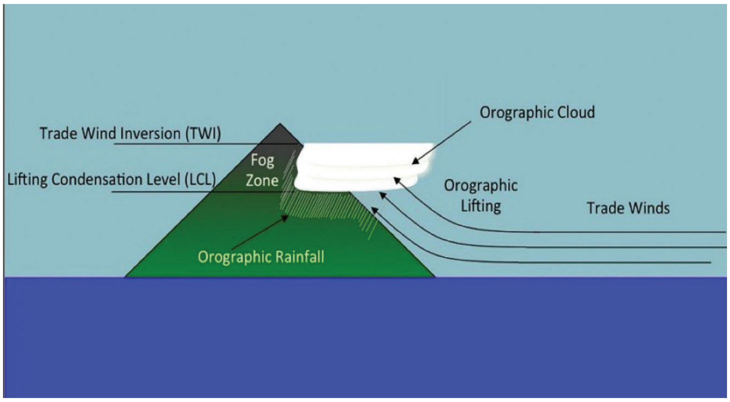


Figure 2-2 Depiction of the orographic effect. The amount and location of rainfall in Hawai‘i and other high islands is strongly controlled by orographic processes. As warm air approaches a mountain range, it rises, cools, and condenses in orographic clouds, causing rainfall. On very high mountains in Hawai‘i, as the cooled air continues to rise, it reaches the trade wind inversion layer, at which point the air again warms, and above which there is little to no precipitation. (From Giambelluca et al., 2011.)

Surface runoff on high islands is channeled into streams in valleys and gulches carved into the mountains by erosion. Groundwater exists in freshwater lenses typical of islands but may also exist as high-level groundwater (Figure 2-1). Groundwater is often the main source of drinking water on high islands; surface water from streams is used for agriculture and to supplement drinking water, but it is also important for ecosystems, culture, recreation, and aesthetics.

Low islands

Low islands include atoll islands and other islands that rise only a few feet above sea level. Unlike the high islands, the low islands do not have sufficient altitude to generate orographic rainfall; therefore, precipitation on these islands is similar to that of the surrounding ocean. Low islands are much more vulnerable to variations or trends in precipitation patterns (especially drought) as they lack the amount of land mass needed for significant hydrological storage and are spatially isolated from other sources of water. Many low islands in the Pacific have a dual-layer aquifer that limits the thickness of the freshwater lens (Bailey & Jenson, 2011). Most low islands do not have streams, and residents are dependent on small, fragile freshwater-lens systems and rainfall catchments for their drinking water. During periods of low rainfall, however, rainfall catchment supplies become depleted and residents commonly rely solely on groundwater from the freshwater lens.

Most low islands in the Pacific have a dry season with a duration that increases with distance from the equator (Lander & Guard, 2003; Lander & Khosrowpanah, 2004; Lander, 1994, 2004). Droughts increase demand on low islands' limited freshwater resources, while sea-level rise, intense storms, and extreme tides threaten water quality and local agriculture, making these communities some of the most sensitive to climate-induced changes in water supply.

Historic and current trends

To fully assess the impact of climate variability and change and accurately predict future conditions in each sub-region, it is necessary to understand current and historic trends in climate and hydrologic records. For each sub-region, trends in observed data are discussed for four general types of records: (1) air temperature, (2) precipitation, (3) extreme precipitation, and (4) streamflow and groundwater. Records such as temperature and rainfall are direct indicators of trends in climate. From these basic records, information on extreme precipitation events such as droughts or large storms can be extracted to provide important insight on how climate change can affect water resources. A common measure for drought is consecutive dry days (CDDs). Measures for extremely high precipitation include the frequency of high- and moderate-intensity rainfall events, the frequency of typhoons and other storms, and the total rainfall over a specified number of consecutive rainy days.

Trends in streamflow records offer a means to assess the impact of climate change on water resources. Streamflow includes water from precipitation that runs directly off the land surface as well as water that discharges from groundwater. The groundwater component of streamflow is known as base flow. Trends in total streamflow primarily reflect trends in surface-runoff rates, whereas base-flow trends reflect changes in groundwater recharge and storage. Trends in the number of extreme high-flow days that occur each year reflect trends in storm frequency, whereas trends in the number of extreme low-flow days reflect trends in drought frequency. Examination of trends in streamflow thus offers a means to assess the impact of climate variability and change on both surface-water and groundwater resources.

Central North Pacific: Hawai'i

AIR TEMPERATURE. Generally, air temperature has increased significantly throughout the State of Hawai'i at both high and low elevations over the last century (Giambelluca et al., 2008). From 1919 to 2006, average temperature for all stations in Hawai'i increased by 0.04°C (0.08°F) per decade (Figure 2-3). The rate of warming accelerated to 0.16°C (0.30°F) per decade from 1975 to 2006 (Giambelluca et al., 2008). The rate of increasing temperature from 1975 to 2006 is greater at high-elevation stations (0.27°C or 0.48°F per decade at greater than 0.5 miles or 800 meters above sea level) (Figure 2-3) and has been documented on the ecologically sensitive peaks of Haleakalā and Mauna Loa on Maui and Hawai'i Island, respectively, where the annual number of below-freezing days has decreased between 1958 and 2009 (Giambelluca et al., 2008; Diaz et al., 2011).

Much of the temperature variation prior to 1975 in Hawai'i appears to have been tightly linked with the Pacific Decadal Oscillation (PDO) (Giambelluca et al., 2008). Since 1975, however, air temperature in Hawai'i has risen at a faster rate that cannot be explained by the PDO (Figure 2-4) and may indicate the increased influence of global warming (Giambelluca et al., 2008). An increase in the frequency of occurrence of the TWI over Hawai'i since the late 1970s (Cao et al., 2007) is consistent with continued warming and drying trends throughout Hawai'i, especially for high elevations. The frequency of occurrence of the TWI over Hawai'i Island and Kaua'i increased during the 1990s from less than 80% to around 90% of the time (Cao et al., 2007).

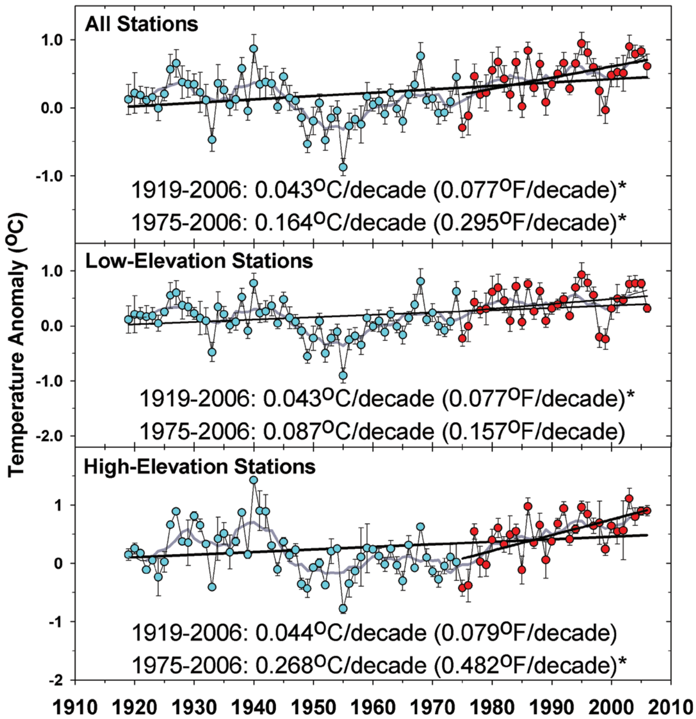


Figure 2-3 Annual average surface temperature anomalies are increasing at both high- and low-elevation stations in Hawai'i (a total of 21). Temperature anomalies are calculated first as the departure from the monthly mean and then averaged into a calendar year. Anomalies greater than zero indicate temperatures that are above average, while anomalies less than zero indicate below-average temperatures. A seven-year running-mean filter (curved line) has been applied to the data to create a smoothed trend curve (black line). Linear trends have been computed for two periods, 1919–2006 and 1975–2006, where the latter period shows the observed enhanced warming. The steeper warming trend in high-elevation stations (>800 meters or >0.5 mile) is visible in the bottom panel, especially when compared to that of the low-elevation stations in the middle panel (<800 meters or <0.5 mile). Error bars show a standard deviation of +0.5. Asterisks indicate slopes significant at p = 0.05. (© 2008 American Geophysical Union. Reproduced/modified from Giambelluca et al. [2008]) by permission of American Geophysical Union.)

PRECIPITATION. In Hawai'i, precipitation can manifest as rainfall, fog, hail, and snow. Mean annual precipitation over the state is highly variable, from 200 mm (about 8 inches) near the summit of Mauna Kea to over 10,000 mm (about 400 inches) on the windward slope of Haleakalā, Maui, and can differ substantially between windward and leeward sides of each island (Giambelluca et al., 2011). The dry summer season lasts from May to October, while the winter rainy season extends from November to April. Although precipitation varies from one area of an island to another, a general downward trend in amount statewide over the last century has been documented, and an even steeper decline is evident since 1980 (Figure 2-5) (Oki, 2004; Chu & Chen, 2005; Diaz et al., 2005, 2011; Giambelluca et al., 2011; Elison Timm et al., 2011). This decline in rainfall and

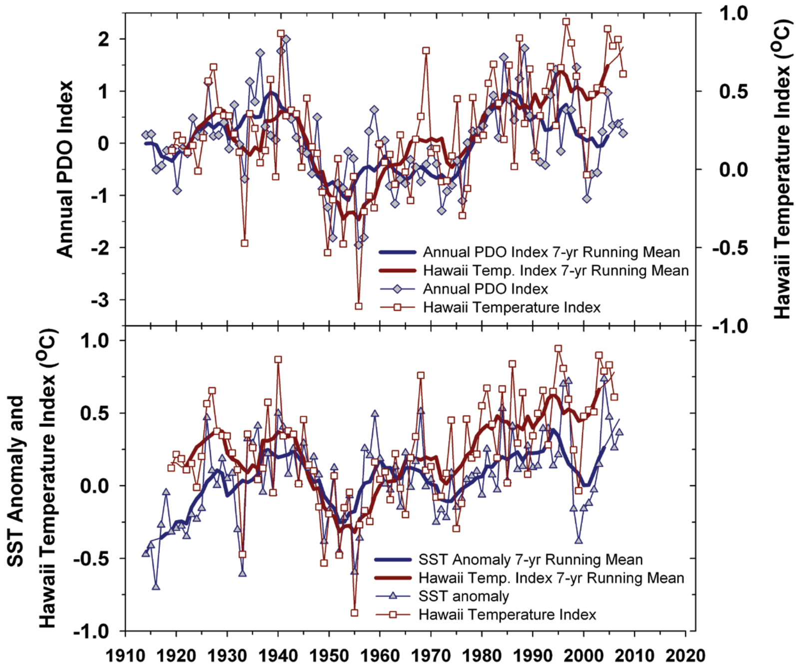


Figure 2-4 TOP PANEL—Air Temperature in Hawai'i (red line) prior to 1975 is tightly coupled to the Pacific Decadal Oscillation (PDO) (blue line). Since 1975, air temperature (red line) has diverged increasingly from the observed PDO, which may indicate the increasing influence of climate change in the Central North Pacific sub-region. BOTTOM PANEL—Local sea-surface temperature anomalies (blue line) for 22°N, 156°W based on the Extended Reconstructed Sea-Surface Temperatures (ERSST) data set (Smith & Reynolds, 2004) are also coupled to air temperatures (red line) in Hawai'i and show a similar decoupling around 1975. (©2008 American Geophysical Union. Reproduced/modified from Giambelluca et al. [2008] by permission of American Geophysical Union.)

corresponding increased rate of warming at high elevations since 1975 is consistent with an increase in the frequency of occurrence of the TWI (Cao et al., 2007; Diaz et al., 2011).

Precipitation variability in Hawai'i is also strongly affected by ENSO and the PDO. ENSO-scale patterns affect interannual variability, such as El Niño events' strong association with dry winter conditions, whereas the PDO affects interdecadal variability (Chu & Chen, 2005). After air temperature and PDO diverged in 1975, initial evidence suggests that precipitation trends are following the same pattern of decoupling (Frazier et al., 2011). Climate change can affect ENSO and PDO patterns; this introduces greater uncertainty into predictions of future precipitation in Hawai'i.

EXTREMES IN PRECIPITATION. To reduce uncertainty in predicting future shifts in regional extreme precipitation, research has improved understanding of historic trends in extreme precipitation and drought on the Hawaiian Islands. Precipitation can be measured both in relative intensity and in probability of occurrence, amount, and total amount over consecutive rainy days. Throughout the state, trends indicate fewer extremely high rainfall events: comparing data from the period of 1950–1979 with data

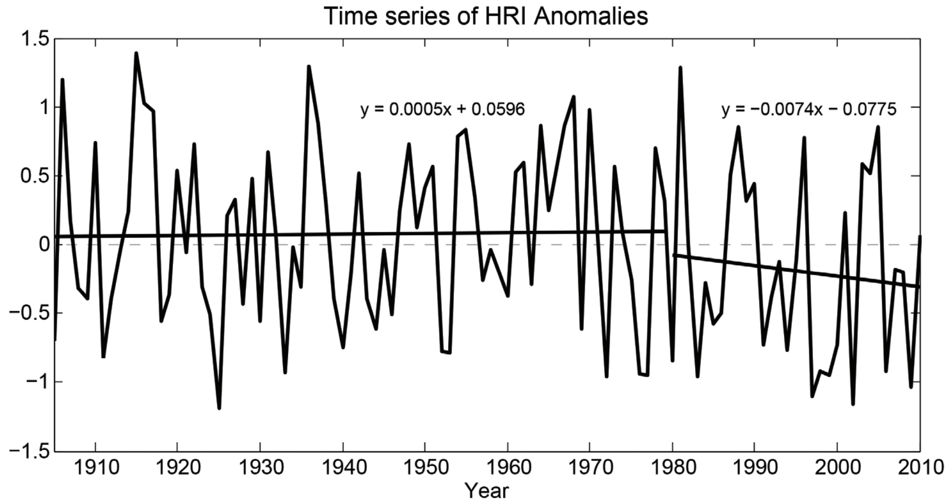
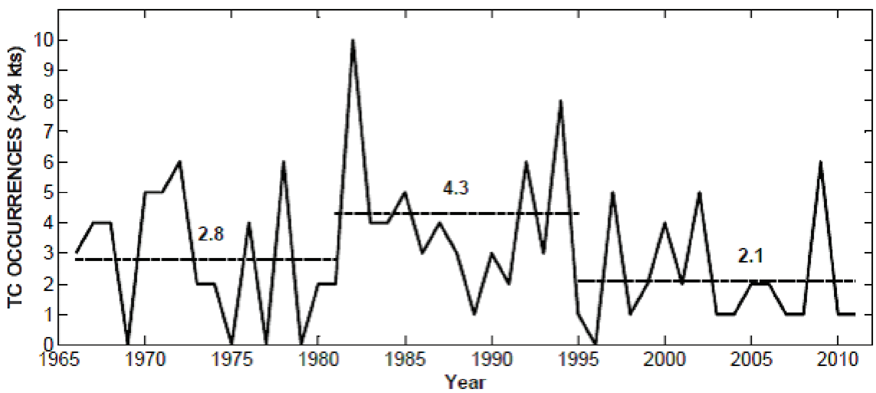


Figure 2-5 Annual normalized and dimensionless (July to June) time series of the Hawai'i Rainfall Index (HRI) from 1905 to 2010. As shown in the plot, the trend for the first epoch (1905–1979) is basically flat, while for the second epoch (1980–2009) the decreasing trend is apparent. Nine stations each from Kaua'i, O'ahu, and Hawai'i are used. These 27 stations represent the spatial variability of rainfall with regard to trade wind exposure and elevation. (Updated from Chu & Chen, 2005.)

from the period of 1980–2011 shows a significant decrease in the frequency of moderate- and high-intensity precipitation events and a corresponding increase in low-intensity events (Chu et al., 2010). Not surprisingly, individual islands show different trends. In terms of extreme storms, the Central North Pacific region may have entered a period of fewer annual tropical cyclones since the mid-1990s (Chu, 2002) (Figure 2-6). All the major Hawaiian Islands have shown a propensity toward longer dry periods, with an increasing annual maximum number of consecutive dry days from the period of 1950–1970 to 1980–2011 (Chu et al., 2010) (Figure 2-7).

Figure 2-6 Time series of tropical cyclones (tropical storms and hurricanes) in the Central North Pacific basin from 1966 to 2010. Although a period of greater tropical cyclone activity occurred from the 1980s to the mid-1990s, the basin has again entered a quieter period, with fewer average annual occurrences of storms. Broken lines denote the means for the periods 1966–1981, 1982–1994, and 1995–2010. (Modified and updated from Chu, 2002.)



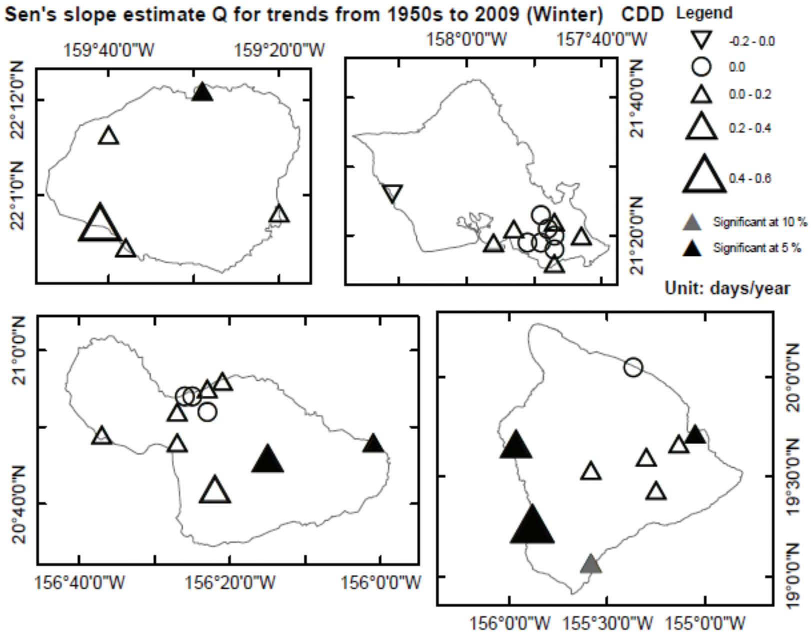


Figure 2-7 All four major Hawaiian Islands (O'ahu, Kaua'i, Maui, and Hawai'i Island) have experienced increasing winter drought severity since the 1950s, defined by a longer annual maximum number of consecutive dry days. Upward triangles denote the increasing drought trends, while downward triangles indicate decreasing trends. Black triangles are significant at the 5% level, and gray at the 10% level. (From Chu et al. [2010] by permission of American Meteorological Society.)

STREAMFLOW AND GROUNDWATER. Streamflow gauges have been operated for nearly a century in Hawai'i with nine stream gauges of nearly continuous record since 1913. These long-term gauges are located on Kaua'i, O'ahu, Moloka'i, and Maui, in both windward and leeward basins and in areas that are unaffected by artificial diversions, reservoirs, or pumping from wells. Eight of the nine gauges show statistically significant downward trends in base flow (the groundwater contribution to streamflow) from 1913 to 2008 (Oki, 2004; Bassiouni & Oki, 2012) (Figure 2-8). Over the last century, the downward trends indicate declines in the long-term mean base flow of 20% to 70%. Short-term cyclic patterns corresponding with ENSO and PDO cycles are superimposed on the downward base flow trends, but these cycles are not the cause of the overall downward base flow trend observed since 1913. The causes of the long-term base flow decline are related to long-term changes in rainfall and possibly evapotranspiration and their relationship to groundwater recharge. In addition, the impact of invasive tree species on streamflow remains largely unknown in Hawaiian forests.

The downward trend in base flow coincides with the statistically significant downward trend in rainfall measured in Hawai'i since 1905 (Chu & Chen, 2005; Diaz et al., 2011; Kruk & Levinson, 2008). The number of days per year with extremely low flow also shows a statistically significant upward trend at most gauges, which is consistent with an upward trend in drought occurrence since the 1950s (Chu et al., 2010). Base flow also may be reduced by processes related to groundwater recharge, such as

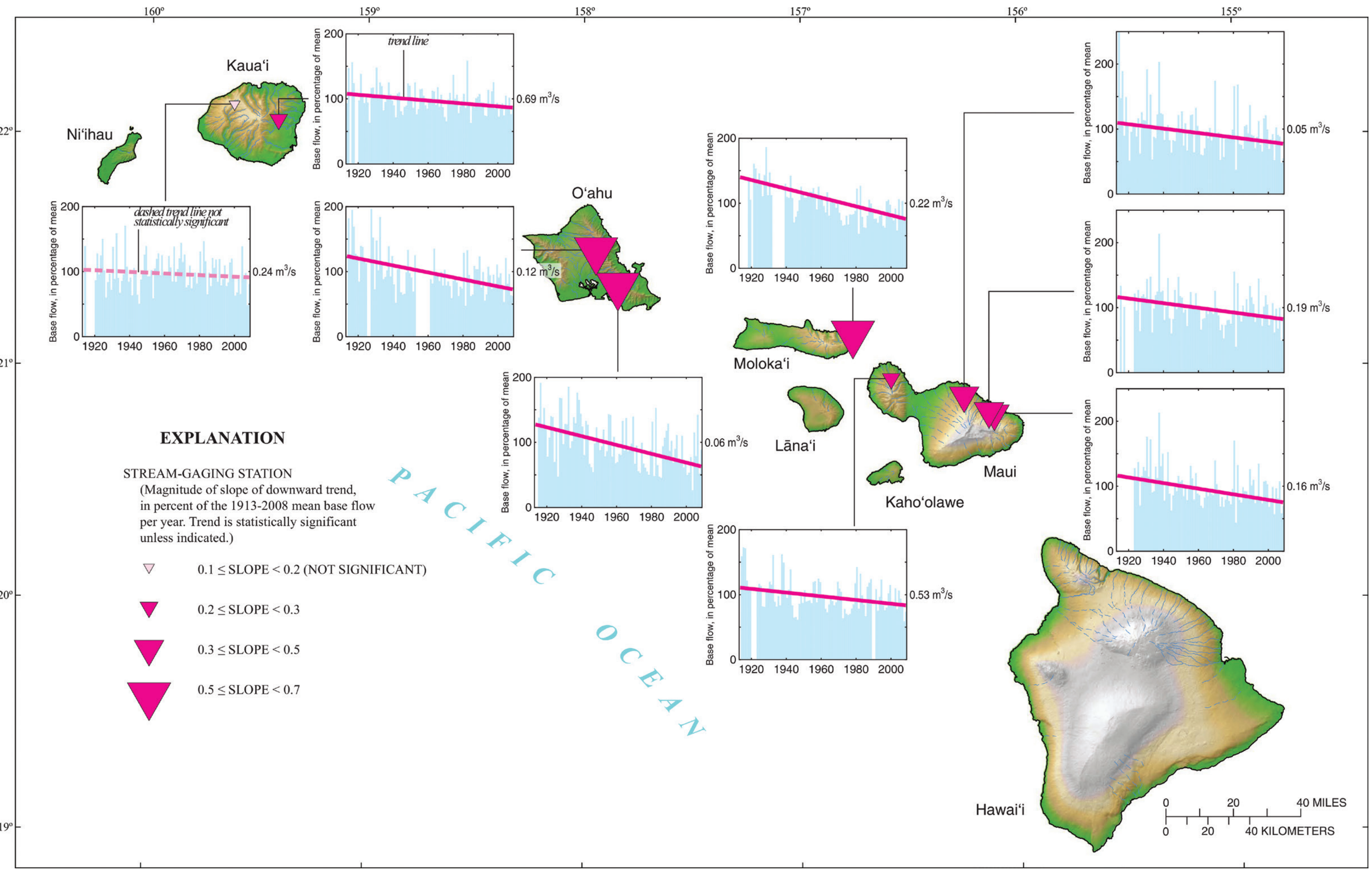


Figure 2-8 Base flow at eight out of the nine long-term streamflow gauges in Hawai'i shows significant decreases of 20% to 70% over the past 100 years. This downward trend is consistent with significant decreases in rainfall in Hawai'i. Because base flow comes from groundwater, decreasing base flow indicates decreasing groundwater resources; this has serious implications for Hawai'i, where 99% of drinking water comes from groundwater (Oki, 2004; Bassiouni & Oki, 2012). (From Oki, 2004.)

Box 2-1

The Hawai'i Water Code: Providing a strong basis for management and planning

In the Hawai'i State Constitution, all public natural resources are held in trust by the State for the people, but only one gets its own section—freshwater. Article XI, Section 7, mandates the creation of "a water resources agency" with broad responsibilities:

> *The State has an obligation to protect, control and regulate the use of Hawai'i's water resources for the benefit of its people. The legislature shall provide for a water resources agency which, as provided by law, shall set overall water conservation, quality and use policies; define beneficial and reasonable uses; protect ground and surface water resources, watersheds and natural stream environments; establish criteria for water use priorities while assuring appurtenant rights and existing correlative and riparian uses and establish procedures for regulating all uses of Hawai'i's water resources.*

The Hawai'i Water Code and Water Commission were established in 1987 to fulfill these constitutional requirements. In addition, the Constitution requires that the Water Code and Commission should settle water-related disputes while protecting traditional cultural rights of Native Hawaiians and the right of every citizen to a clean, healthy environment.

By including language that calls for integrated management of water resources, forward-looking and proactive policy, continuous monitoring, and preservation and enhancement of natural systems, the Water Code is written with inherent adaptive characteristics (Wallsgrove & Penn, 2012). By definition, adapting to climate change requires this type of forward-looking and multidisciplinary approach. Thus, the law and policy framework for water resource management in Hawai'i may be well poised to respond quickly to the facts of changing local climates. With appropriate funding, staffing, and support, these adaptive characteristics could allow the Commission and policymakers in Hawai'i to create a management regime that is well-suited to reflect the most recent advances in scientific understanding, as well as political and economic conditions, while protecting a crucial natural resource for current and future residents of Hawai'i.

evapotranspiration (Bassiouni & Oki, 2012). The downward trends in base flows indicate a decrease in groundwater discharge to streams, which implies a decline in groundwater recharge and storage. This has serious implications for Hawai'i's domestic drinking-water supply, 99 percent of which comes from groundwater (Gingerich & Oki, 2000).

Total streamflow at most gauges showed no significant trend (Oki, 2004). Trends in total streamflow may be obscured by high year-to-year rainfall variability, whereas in the base flow record, this variability is filtered out by the groundwater system.

Box 2-2

High-quality data and monitoring networks are threatened

The continuous collection and storage of hydrological, ecological, and climatological data in the Pacific Islands region is of utmost importance to science and society. As impacts of climate variability and change are observed, long-term records of land and ocean variables can help us identify shifts between average conditions of the past and potential future conditions (Milly et al., 2008). Long-term, reliable, global and local observations of variables such as air temperature, precipitation, sea-surface temperature, streamflow, and groundwater supply are critical to understand the evolving state of the Earth's climate. Having long-term and high-quality scientific data is critical not only for understanding the dynamics of natural processes but also for ensuring the accuracy of models that simulate potential future impacts of climate change and variability. Continuous data collection and stewardship must be maintained to ensure that governments, researchers, and the public have access to reliable, high-quality data.

At the international level during the past several decades, the efforts of the IPCC have brought attention to the deficiency of quality and quantity of monitoring systems (IPCC, 2007). These deficiencies include a lack of consistent standards for instrumentation; poor maintenance and station siting; insufficient instrument calibration; a lack of intercomparability; and inadequate funding (Karl et al., 2010; Manton et al., 2010; Trenberth, 2008). In the Pacific Islands region, researchers are very concerned about the aging and decreasing number of monitoring systems. The majority of the Pacific Islands region is open ocean, making a robust ocean observational network crucial to understanding local climatic phenomena. In addition to monitoring the ocean, land-based networks of long-term stream and rainfall gauges; temperature, evapotranspiration, and wind stations; and vegetation maps are equally essential. For example, the number of active rain gauges in Hawai'i decreased from 1,030 in 1968 to only 340

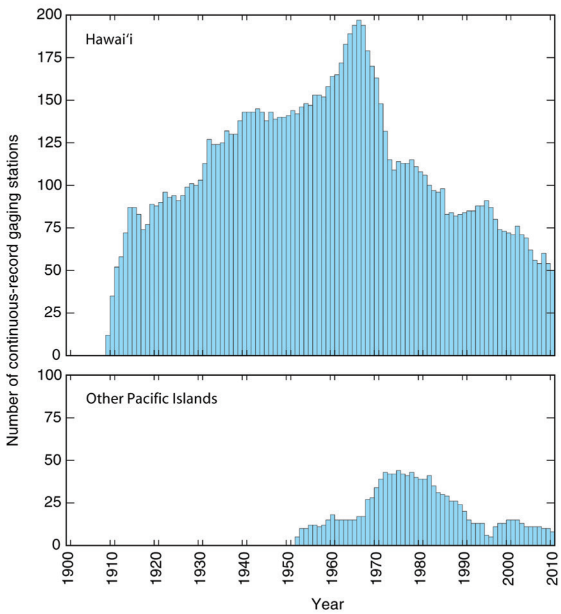


Figure 2-9 In the Pacific Islands, the number of continuously operating streamflow gauging stations has been steadily declining since the 1960s and 1970s, which parallels the decline of other essential climate variable monitoring networks in the region. Hawai'i has been fortunate to have streamflow records with about a century of data, although recent financial cuts are threatening even these essential networks. (Figure courtesy of Delwyn Oki.)

Box 2-2 (Continued)

in 2007 (Giambelluca et al., 2011), while numbers of USGS streamflow gauges have been declining since the mid-1960s and 1970s throughout the Pacific Islands Region (Oki, 2004), threatening to introduce discontinuities in rare and high-quality century-long records (Figure 2-9).

Within the Pacific Islands, streamflow has been monitored in Hawai'i, American Sāmoa, Guam, the CNMI, Republic of Palau, and the FSM. Hawai'i has the most streamflow data in terms of record length, number of gauges, and area covered (Oki, 2004). Some stream gauges in Hawai'i have been in continuous operation since about 1910. The rest of the Pacific Islands region has much less data, with gauges only on the most populated or largest island in each political entity, and records extending back only to the 1950s and most ending in the 1990s. Besides Hawai'i, only Guam has stream gauges in operation as of 2011. Continuation of streamflow monitoring in Hawai'i and Guam and re-establishment of monitoring of ocean and terrestrial climate variables in other island groups are critical to assessing the impact of climate change on the water resources of the Pacific Islands region and the communities and economies they support.

Western North Pacific

West: Guam, RP, FSM (Yap, Chuuk), CNMI; **East:** FSM (Pohnpei, Kosrae), RMI

AIR TEMPERATURE. At least one station on each major island group has a relatively complete and continuous record since 1950, whereas other stations have very short records with many gaps. Across all recorded temperatures, however, observed maximum and minimum temperatures have exhibited increasing trends over the past 60 years (Figures 2-10 and 2-11) (Kruk et al., 2012; Lander & Guard, 2003; Lander & Khosrowpanah,

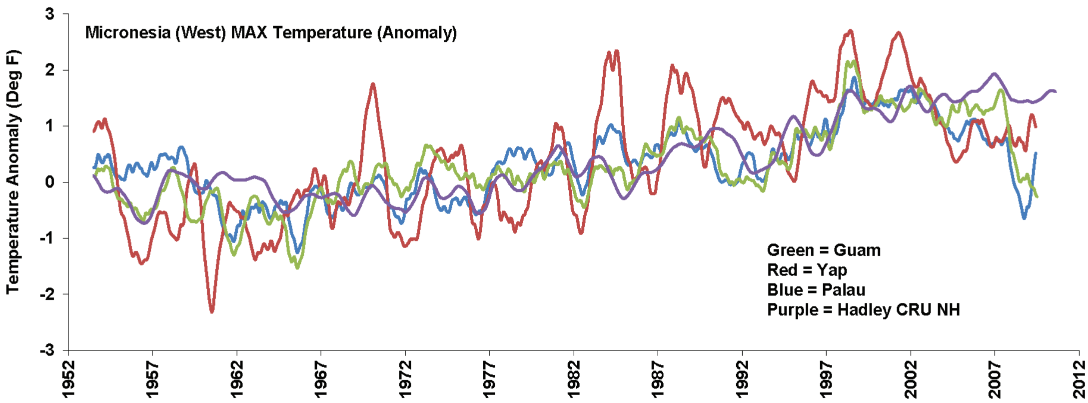


Figure 2-10 Maximum monthly temperature anomaly time series from 1952 to 2012 (using 1960–1990 as the mean reference period) for single monitoring stations with the most data in Yap, Guam, and Palau. The northern hemisphere temperature time series (purple line, Hadley CRU NH) is superimposed for comparison. Trends in maximum temperatures in the western part of the Western North Pacific subregion appear to be increasing at the same general rate as average northern hemisphere temperatures, although Yap shows a high level of variability. (Updated from Lander & Guard, 2003.)

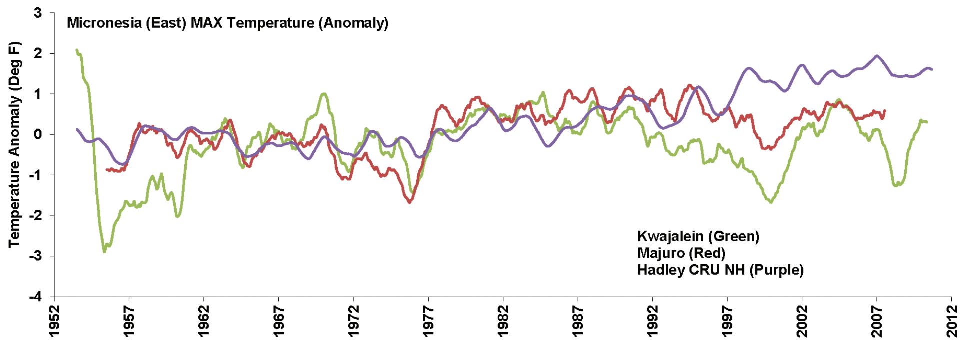


Figure 2-11 Maximum monthly temperature anomaly time series from 1952 to 2012 (using 1960–1990 as the mean reference period) for single monitoring stations with the most data in Kwajalein and Majuro in the RMI. The northern hemisphere temperature time series (purple line, Hadley CRU NH) is superimposed for comparison. Trends in maximum temperatures in the eastern part of the Western North Pacific sub-region have high levels of variability and may reflect issues in the quality of the data or station infrastructure. (Modified and updated from Lander & Guard, 2003.)

2004; Lander, 2004). The large interannual variability shown in Figures 2-10 and 2-11 is partly related to a strong correlation of air temperature with ENSO conditions—most of Micronesia is cooler than average during the El Niño phase of ENSO and warmer during the La Niña phase. The westernmost Micronesian island groups of Yap, Guam, and Republic of Palau (RP) show trends that generally track observed temperature trends in the northern hemisphere but with more variability (Figure 2-10) (Jones et al., 1999; Brohan et al., 2006; Lander & Guard, 2003). The Majuro Weather Office has identified accelerated trends in maximum temperatures in the RMI since 1973, with a rise of about 0.14°C (0.25°F) over the past 30 years (Jacklick et al., 2011). In the same 30-year period, trends in minimum temperatures have been increasing more slowly, at about 0.12°C (0.22°F) (Jacklick et al., 2011). In both the western and eastern Micronesian island chains, the rate of increase in maximum temperatures has become less steep since 2000. These declines may have to do with shifts in large-scale climate phenomena after the major El Niño event of 1998 (Chavez et al., 1999) or may reflect station relocation. Many of the longest and most complete records of air temperature in the Western North Pacific sub-region (WNP) are at airports and military bases, which may introduce the complicating factors of paved surfaces and artificial heat sources into the record. A continuing analysis of the veracity of data collected from different types of station sites on the continental United States shows no evidence that poorly situated stations collected artificially inflated air temperature data (Menne et al., 2010); however, this analysis was not extended to stations in the Pacific Islands region.

PRECIPITATION. Islands throughout the WNP tend to receive abundant rainfall. Islands at lower latitudes, such as Chuuk, Pohnpei, Kosrae, and some low islands in the Republic of the Marshall Islands (RMI), receive over 3,000 mm (about 118 inches) of rainfall annually, which is stored in catchments as an important source of drinking and irrigation water (Lander & Khosrowpanah, 2004; Bailey & Jenson, 2011). All islands have a wet season and a dry season, with the relative length and intensity of each season depending on latitude. The more northward the island, the longer and drier the dry season tends to be. As with the variability in air temperature, ENSO has a strong effect on precipitation in Micronesia, with strong El Niño events corresponding closely with an increased risk for drought in the following year. Eastern Micronesian islands such as Majuro and Kwajalein show a statistically significant drying trend from 1954 to 2011, such that over the past 60 years, these islands have lost nearly 15 percent of their annual rainfall, while western Micronesian islands show a slight tendency toward wetter conditions (Figure 2-12) (Bailey & Jenson, 2011; Jacklick et al., 2011). On the westernmost islands such as Yap and RP, precipitation shows upward trends, but the trends are not statistically significant (Kruk et al., 2012).

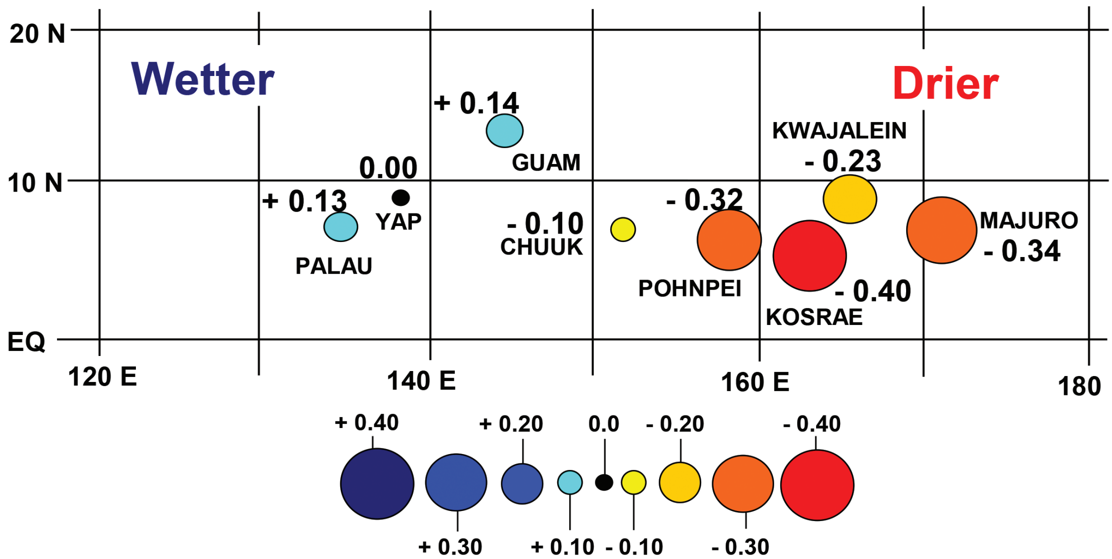


Figure 2-12 Annual rainfall anomaly (inches per month per decade) in the WNP sub-region from 1950 to 2010 shows that whereas islands in the west are tending toward getting slightly more precipitation, islands in the east are experiencing much less precipitation. Darker blue shading indicates wetter conditions, and darker red shading indicates drier. The size of the dot is proportional to the size of the trend as per the inset scale. (Modified and updated from Lander & Guard, 2003, and Lander, 2004.)

EXTREMES IN PRECIPITATION. Although islands in the WNP have large amounts of rainfall annually, drought is a serious issue throughout Micronesia because of limited storage capacity and small groundwater supplies. During the winter and spring months following an El Niño, drought tends to be the most extreme. Limited research has been conducted on trends in extreme precipitation throughout Micronesia, although some results indicate fewer extreme rainfall events greater than 254 mm (10 inches) in 24 hours in Guam and the Commonwealth of the Northern Mariana Islands (CNMI) since the 1950s (Lander & Guard, 2003; Lander & Khosrowpanah, 2004). Preliminary region-wide analysis indicates that both summer and winter one-day amounts of precipitation over the 95th percentile have been declining since the early 1900s (Kruk et al., 2012).

A more controversial issue for the sub-region is the trend in distribution and frequency of tropical cyclones (Knutson et al., 2010). Although attribution of an individual cyclone to climate change would be tenuous, shifts in storm frequency in both the Western North Pacific basin and other basins around the world have destructive impacts on island nations. The WNP basin is the world's most prolific typhoon basin, with an annual average of 25.8 (Japan Meteorological Agency data) or 26.3 (Joint Typhoon Warning Center data) named tropical cyclones between 1951 and 2010, depending on the database used (Knapp et al., 2010). Since 2000, the basin has been very calm, with only 14 numbered storms in 2010 (Knapp et al., 2010) (Figure 2-13). Typhoons tend to be more intense in El Niño years, especially in the eastern regions of Micronesia. Research into how future climate will affect the frequency and intensity of tropical storm systems is of great societal importance for Pacific Islanders' food and water supplies, livelihoods, and health (Gualdi et al., 2008).

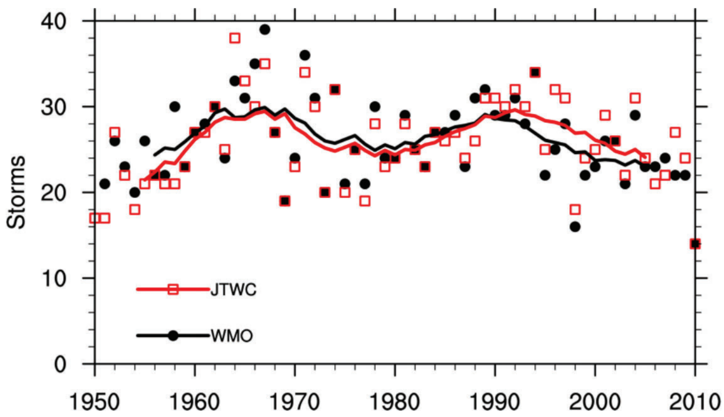


Figure 2-13 The number of tropical cyclones in the WNP basin as observed by the World Meteorological Organization (WMO; black lines/dots) and the Joint Typhoon Warning Center (JTWC; red lines/dots) since 1950. Lines indicate smoothed storm trend. There are regular cycles of greater and lesser annual storm numbers, and there were only 14 named storms in 2010. (From Knapp et al. [2010] by permission of American Meteorological Society. Data from the International Best Track Archive for Climate Stewardship [IBTrACS].)

STREAMFLOW AND GROUNDWATER. Streamflow records available for the WNP are short relative to those in Hawai'i, mostly discontinuous, and many have been affected by upstream diversions or other human activities. The longest record (57 years) and the most complete record (49 years) are from Guam (Miller et al., 2012). Only two gauges on Guam have more than 35 years of record and are unaffected by artificial diversions. Neither of the records from these gauges shows a significant trend in total streamflow, base flow (Figure 2-14), or the number of extreme low-flow or high-flow days. The lack of significant streamflow trends on Guam is consistent with a similar lack of trends in rainfall observations (Kruk et al., 2012; Lander & Guard, 2003; Lander & Khosrowpanah, 2004; Lander, 2004).

Due to the vulnerability of many low islands in the Western North Pacific to drought, it is important to assess the capacity and potential resilience of freshwater-lens systems across the region. Studies modeling observed groundwater conditions in selected atolls

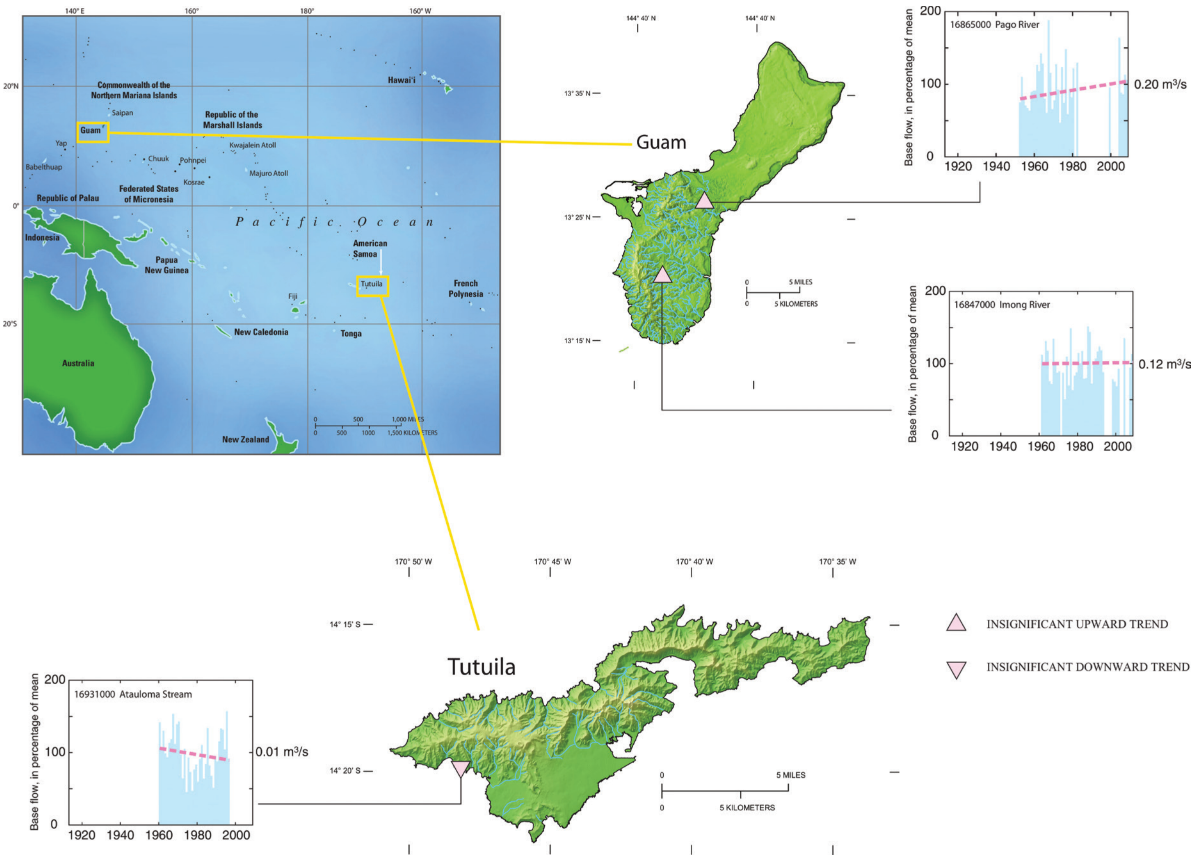


Figure 2-14 Streamflow records available for the Western North Pacific and Central South Pacific sub-regions are relatively short and mostly discontinuous, and many have been affected by upstream diversions or other human activities. Analysis of data from 1978 to 2008 from two gauges on Guam and one on Tutuila, American Samoa, showed no statistically significant trends (red dashed line) in the number of extreme high- or low-flow days. The lack of significant streamflow trends on Guam and American Samoa is consistent with rainfall observations but may also be an artifact of short record available for analysis, highlighting the need for consistent and high-quality monitoring in these sub-regions. (From Miller et al., 2012.)

in the Federated States of Micronesia (FSM) have demonstrated that during severe drought conditions, only a few large leeward islands are able to maintain a substantial freshwater lens (about 6 percent of the islands studied) (Figure 2-15) (Bailey & Jenson, 2011; Bailey et al., 2010). The quantified limited capacity and fragile nature of these lenses demonstrate the extreme vulnerability of low islands in the sub-region to sustained drought conditions.

Central South Pacific: American Sāmoa

AIR TEMPERATURE. Average air temperatures in American Sāmoa are tropical, ranging from about 21° to 32°C (70° to 90°F). In the Central South Pacific sub-region (CSP),

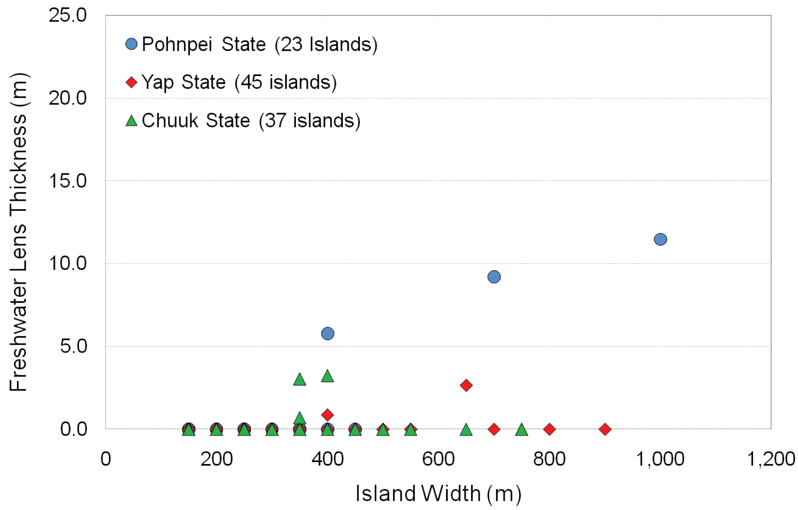


Figure 2-15 Low islands are highly vulnerable to stresses on their freshwater resources in times of drought. Shown here is a plot of the estimated modeled freshwater lens thickness (meters) among atoll islands in the Federated States of Micronesia for drought conditions similar to the severe 1998 event that followed a large El Niño. Under simulated drought conditions, only 6 out of 105 islands will have freshwater lenses thick enough to provide groundwater. (From Bailey & Jenson, 2011.)

average, minimum, and maximum temperatures indicate a general warming trend since the 1950s. The largest observed increase has been in minimum air temperatures, while average temperature increases range from 0.15° to 0.25°C (0.27 to 0.45°F) per decade, depending on the island (Australian Bureau of Meteorology & CSIRO, 2011). Regional analyses of air temperature in Sāmoa are highly variable but also show an upward trend in maximum air temperatures since 1950 (Young, 2007).

PRECIPITATION. American Sāmoa is warm, humid, and rainy all year. The summer season is long and wet, lasting from October to May, and the winter season is only slightly cooler and drier, from June to September. Annual mean rainfall at Pago Pago Airport is about 3,048 mm (120 inches), although other areas can receive as little as 1,800 mm or as much as 5,000 mm (about 71 to 200 inches) due to orographic effect (Izuka et al., 2005). ENSO effects in American Sāmoa and the CSP vary by the strength of the particular anomaly event. During strong El Niño events, the monsoon trough is pulled northward and the SPCZ moves east-northeast of the Sāmoan region, making it significantly drier. In moderate El Niño events, the CSP is more susceptible to tropical cyclone formation and passage, and the rainy season tends to initiate earlier and end later. During weak El Niño events, the monsoon trough and SPCZ are west of the Sāmoa region. This causes reduced tropical storm activity and conditions that are drier than average. In Āpia, Sāmoa (about 80 km or 50 miles west of American Sāmoa), long-term records from 1890 to 2005 show no trend in daily, monthly, or annual precipitation (Young, 2007; Australian Bureau of Meteorology & CSIRO, 2011).

EXTREMES IN PRECIPITATION. Little detailed work has been undertaken examining trends in extreme events in this sub-region. Initial analysis of extreme precipitation records has only been done using the Pago Pago airport rain gauge, which has the longest period of record and the least missing data in American Sāmoa. Nearly all other rain gauges throughout American Sāmoa have been discontinued. Data from the Pago Pago Airport gauge show no trend in annual or winter one-day amounts of precipitation above the 95th percentile since 1965, and summer one-day amounts show a slight downward trend that is not statistically significant (Kruk et al., 2012).

ENSO and tropical cyclones are associated with extreme events in the South Pacific Islands. For the Central South Pacific sub-region, tropical cyclones occur between November and April; the number of cyclones varies widely from year to year but they tend to occur more frequently during moderate-intensity El Niño years and less frequently during weak El Niño events. Additionally, Madden-Julien Oscillation (MJO) propagation, the major source of intraseasonal variability in the tropical atmosphere, intensifies and increases the frequency of tropical cyclones during moderate El Niño events. Lastly, during strong La Niña events, the SPCZ lies far southwest of the Sāmoan region, and the risk of tropical cyclone development is moderate to high. The frequency of extremely high rainfall events per year has remained consistent since 1965 (Kruk et al., 2012).

STREAMFLOW AND GROUNDWATER. Streamflow records available for American Sāmoa are relatively short and mostly discontinuous, and many have been affected by upstream diversions or other human activities. Only one gauge on the main island of Tutuila has more than 35 years of record and is unaffected by artificial diversions (Miller et al., 2012). Data from this gauge did not show a significant trend in total streamflow, base flow, or the number of extreme low-flow or high-flow days (Figure 2-14). Although the lack of significant streamflow trends on American Sāmoa is consistent with a similar lack of trends in rainfall observations (Young, 2007; Australian Bureau of Meteorology & CSIRO, 2011), it may also be an artifact of the lack of sufficiently long streamflow records for this sub-region.

Projections

Although global and regional projections from the 2007 IPCC report are coarse, it is possible to make general projections at a grid scale of 200 by 200 kilometers (about 124 by 124 miles) on drivers of key water-related processes (Christensen et al., 2007). As shown in Chapter 1 ("Models and Projections"; Figure 1-8), mean annual air temperatures in Hawai'i and the Central North Pacific region in three future time periods (2035, 2055, and 2085) for the B1 and A2 emissions scenarios all show an increase compared to 1971–2000. For 2035, temperature increases in the B1 scenario range from +0.6° to 1.1°C (+1° to 2°F), and in the A2 scenario from +0.8° to 1.4°C (+1.5° to 2.0°F) (Christensen et al., 2007; Meehl et al., 2007). In the WNP, projected annual surface air temperature increases range from +0.6° to 0.7°C (+1.1° to 1.3°F) by 2030, +1.0° to 1.4°C (+1.9° to 2.6°F) by 2055, and +1.5° to 2.8°C (+2.7° to 5.1°F) by 2090 for the B1 and A2 emission scenarios (Australian Bureau of Meteorology & CSIRO, 2011). Projections in the CSP also show warming, with annual air temperatures ranging from +0.6° to 0.7°C (+1.1 to 1.3°F) by 2030, +1.0° to 1.4°C (+1.9° to 2.5°F) by 2055, and +1.4° to 2.6°C (+2.5° to 4.8°F) by 2090 for B1 and A2 emissions scenarios (Australian Bureau of Meteorology & CSIRO, 2011).

Projections of future rainfall are more uncertain. As shown in Chapter 1 ("Models and Projections"; Figure 1-8), the best projections for the Central North Pacific sub-region of mean annual rainfall in three future time periods (2035, 2055, and 2085) for the B1 and A2 emissions scenarios as compared to 1971–2000 suggest that by 2085, the southern parts of the region will show large increases in average rainfall of +0.5 to 7.5%, while northern areas will show slight decreases of –0.5 to 1.5%. The magnitude of this south-to-north drying trend will increase as time progresses. Statistical downscaling with much finer resolution over Hawai‘i shows reductions in wet-season rainfall (November to April) (Takahashi et al., 2011) that are consistent with trends indicating increasing winter drought since the 1950s (Figure 2-16), increases in dry-season rainfall, and changes in the frequency of heavy rainfall events in Hawai‘i during the 21st century. However, the number of heavy rainfall days in Hawai‘i during the 21st century is not predicted to increase dramatically, based on the predicted variations in the frequency and magnitude of ENSO and the Pacific–North American pattern (Elison Timm et al., 2011; Norton et al., 2011; Elison Timm & Diaz, 2009).

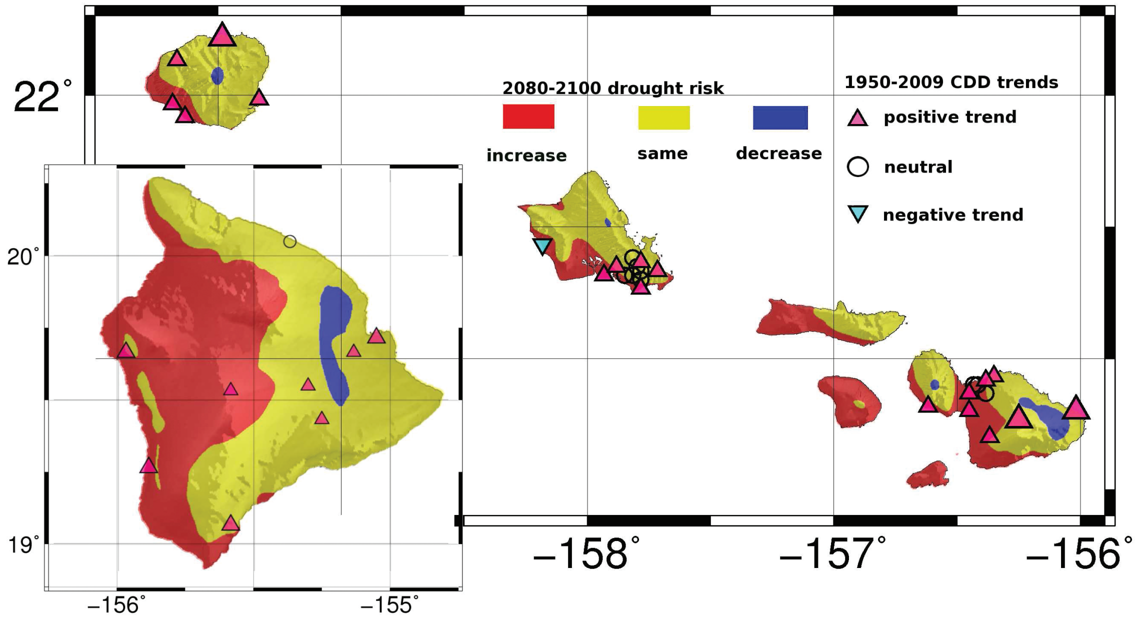


Figure 2-16 All four major Hawaiian Islands (O‘ahu, Kaua‘i, Maui, and Hawai‘i Island) have experienced increasing winter drought since the 1950s, defined by a longer annual maximum number of consecutive dry days. Background colors highlight changes in the number of low-precipitation months during the wet season (November–April) based on statistically downscaled climate change scenarios from six models of the IPCC AR4 report for years 2080–2100. (Figure courtesy of Oliver Elison Timm.)

In the Western North Pacific, rainfall projections suggest that the wet season will get wetter and the dry season drier, with overall increases in mean annual rainfall (Australian Bureau of Meteorology & CSIRO, 2011). Both the intensity and frequency of days of extreme rainfall are projected to increase over the 21st century. Due to variable observed trends in precipitation in the Central South Pacific, projections are less certain. However, models show either no change or a slight decrease in dry-season rainfall and an increase in wet-season rainfall in the 21st century (Australian Bureau of Meteorology & CSIRO, 2011).

Impacts and adaptation

Impacts of climate change on freshwater resources in the Pacific Islands region will vary, not only because of differing island size and height but also because of the relative adaptive capacity and ability to organize of the specific island or community in question. In the Pacific Islands, "communities" have traditionally been separated by dominant landscape features (i.e., mountain ridges, valleys, etc.), traditional land management units, and historical familial land rights. These well-defined geographical boundaries and traditional land and resource management practices contributed greatly to the ability for most communities in the region to organize. In American Sāmoa, for example, local communities are organized into villages, managed by both traditional and western resource and land management practices. In contrast, modern local communities in Hawai'i are typically townships, managed by a complex regulatory system with numerous jurisdictional entities. More recently in Hawai'i, an increased focus has been placed on blending current western systems with more traditional land management techniques.

On high islands such as Hawai'i that are already showing decreases in precipitation and base flow (Oki, 2004), the continuation of these decreasing trends may impact freshwater ecosystems and aquatic species, especially as flows decline so much as to become intermittent. Decrease in streamflow may also interrupt movement of native species along streams and may prevent species that spend their larval stages in the ocean from returning to the streams to complete their life cycle. Invasive plant and animal species are established and expanding in many forests, and their responses to climate change will interact with those of native species to determine future ecosystem composition and processes. Existing climate zones are projected to shift, generally upslope, with some eventually disappearing (Benning et al., 2002). The ability of native plant species to adapt to these changes will be affected by competition with aggressive invasive species and dispersal limitations due to the extinction of many native pollinators and seed dispersers. Available habitat decreases rapidly with elevation, putting species currently found on upper slopes and ridges at special risk.

In Kahalu'u, Kona, Hawai'i, a watershed and ecosystem adaptation project illustrates the importance of maintaining a healthy freshwater system using local, informed perspectives of water resources from the forest to the ocean. Led by the University of Hawai'i at Mānoa and The Kohala Center, the project is working to create useful tools for freshwater management through local community involvement. An aim of the project is for the community to better understand freshwater movement through the environment to the surface-water features of the Kona coast in order to emphasize the importance of maintaining a healthy and functioning ecosystem (The Kohala Center, 2008).

Climate will continue to affect human health on the Pacific Islands. Low islands and coastal communities in the WNP sub-region are especially vulnerable due to their low elevation, small land mass, geographic isolation, and limited potable water sources and agricultural resources (Barnett & Adger, 2003). Sea-level rise and more frequent inundation by king tides and tropical cyclones may not only contaminate limited groundwater resources but also overcome basic sanitary systems and agricultural fields (see Case Study 2-1 at the end of this chapter). Given that many vector- and water-borne diseases are weather-influenced, climate change impacts on low islands and coastal communities allow for malaria, dengue (Kolivras, 2010), diarrhea, and other diseases to increasingly infect some Pacific Island populations. The young, the elderly, and those with preexisting medical conditions are especially vulnerable to these diseases (World Health Organization, 2010).

It is very likely that agriculture and food security will be impacted by climate change through increased drought, possible increases in storm intensity, and changes in rainfall patterns (Sivakumar & Hansen, 2007). The potential increased intensity of storms and cyclones may result in significant damage to agricultural infrastructure such as crop- and water-storage facilities, irrigation systems, roadways, heavy equipment, and low-lying crop areas. Increased temperatures coupled with decreased rainfall may lead to additional need for freshwater resources for crop irrigation (Döll, 2002). This is particularly important for locations in the tropics and subtropics where observed data and model projections show a high probability (>90%) that growing-season temperatures by the end of the 21st century will exceed the most extreme seasonal temperatures recorded from 1900 to 2006 (Battisti & Naylor, 2009). Although the Pacific Islands may be more vulnerable to climate impacts because of their small size and isolation, some island communities have effectively acclimated to changes in climate over time. For example, while climate impacts such as drought, saltwater inundation, and increasing water temperature will have impacts on traditional food sources such as taro and breadfruit (Maclellan, 2009), there are projects to address the observed reduction in upland garden and taro yields (Wongbusarakum, 2010).

In terms of economic impacts, changes in the climate will affect tourism, a main source of income for many islands throughout the Pacific. Tourism is an extremely water-intensive economic activity that may suffer from changes in island freshwater supplies (Christensen et al., 2007). Infrastructure for water delivery and sewage is also vulnerable to climate-related flooding and erosion and poses additional risks to island populations as a result of extreme events (storms and droughts) and sea-level rise, which contribute to drinking water contamination and sewage overflow. For example, in December 2010, heavy storms caused multiple sewer overflows and pipe breakages on the island of O‘ahu in the State of Hawai‘i. As storm intensity and frequency are predicted to change in some Pacific Island sub-regions and storm paths may shift (Australia Bureau of Meteorology & CSIRO, 2011), reliance of the majority of the Pacific Islands on imported oil for primary energy production renders them highly vulnerable to climate-related disruption of delivery and subsequent energy production. Because the Pacific Islands are almost entirely dependent on imported food, fuel, and material (Austin et al., 2011; Hawai‘i State Civil Defense, 2010), the vulnerability of ports and airports to extreme events, especially typhoons, is of high concern.

There are organizations that increase the knowledge base of water managers through the entire region and strive to enhance their adaptive capacity. For example, the Pacific ENSO Applications Climate (PEAC) Center has been producing information products on climate variability for island water managers for all US-Affiliated Pacific Islands since 1994 (PEAC Center, 2010). The PEAC Center provides free quarterly electronic and hard copy newsletters with seasonal forecasts of rainfall, storms, and the latest ENSO conditions that are sub-regionally applicable.

Summary

Islands and atolls in the Pacific have unique issues relating to freshwater resources. Data indicate that the Pacific Islands are being affected by climate change and variability and are vulnerable to future impacts. Due to their small size, exposure to the ocean, lack of economic resources, and isolation, the Pacific Islands are at high risk of experiencing negative climate impacts to already fragile freshwater resources. Assessment of climate change impacts is hampered, however, by decreases in essential monitoring and observation. The problem is so severe that at present this extensive region is monitored by only a handful of reliable stations. Projections of future climate indicate that the negative impacts of climate change are very likely to continue and intensify in the Pacific Islands sub-region over the next century.

The main regional findings of this chapter include the following:

- Because of their small size and isolation, islands in the Pacific have limited and fragile freshwater resources, making them more vulnerable to climate hazards and stresses than are continents.
- Freshwater resources on low islands are especially vulnerable to climate-related threats due to their small size and limited natural and socio-economic resources.
- The strong influence of the El Niño-Southern Oscillation in the Pacific superimposes natural short-term cyclic variations on long-term trends in precipitation. This makes it difficult to detect long-term regional climate trends and make accurate predictions.
- There are now fewer long-term monitoring stations in the Pacific than there were a few decades ago. To accurately assess trends in water resources as climate changes, more data and basic monitoring are severely needed.

In the Central North Pacific sub-region:

- Average air temperature in Hawai‘i has risen significantly in the past 100 years. This rise in air temperature has accelerated in the past 30 years.
- Increasing air temperature is more rapid in high-elevation environments located more than a half mile above sea level.
- Annual precipitation has decreased significantly in the past 100 years.
- In the past 30 years, all Hawaiian Islands have experienced greater numbers of consecutive dry days and fewer days of intense rainfall.
- Base flow, the groundwater component of streamflow, has shown significant downward trends of 20% to 70% in the past 100 years. This trend indicates a decrease in groundwater resources.
- The sub-region has experienced a decrease in climate monitoring stations. The ability to assess future climate changes in meaningful detail is at risk.

In the Western North Pacific sub-region:

- Although variability is high, maximum and minimum air temperatures have exhibited upward trends over the past 60 years.
- Eastern Micronesian islands such as Majuro and Kwajalein have shown a significant downward trend in rainfall over the past 60 years, while western Micronesian islands show non-significant trends toward more precipitation. In the past 60 years, there have been fewer extreme one-day rainfall events in Guam and the CNMI.
- The smallest islands are extremely vulnerable to droughts of any severity.
- The sub-region suffers from a declining number of climate monitoring stations and is currently not adequately instrumented to assess future climate changes in meaningful detail.

In the Central South Pacific sub-region:

- In the past 60 years, average, minimum, and maximum air temperatures have been increasing. The largest observed increases have been in minimum air temperatures.
- In Sāmoa, precipitation records in the past 100 years have shown no trend.
- The frequency of extreme precipitation and drought events has not changed significantly in the past 60 years.
- No significant trends were detected in streamflow, which may be due to the short length of record.
- The region suffers from a declining number of climate monitoring stations and is currently not adequately instrumented to assess future climate changes in meaningful detail.

FOCUS ON ADAPTATION

Case Study 2-1

Managing vulnerable water resources in atoll nations

Water supplies on small, low-lying atoll islands are extremely vulnerable to droughts and to saltwater inundation caused by high tides. Water for drinking and other uses comes from two sources: rainwater catchments and shallow wells that draw from a layer or “lens” of freshwater that is underlain by brackish water or saltwater. Groundwater in the part of the lens that is near the ground surface in the central depression of the island is also important for taro cultivation. On some atoll islands, the freshwater lens is thin and highly vulnerable to contamination from the saltwater below, especially if too much freshwater is drawn from the lens.

The El Niño event of 1997–1998 caused severe droughts and water shortages on many of the Pacific Islands. Between January and April 1998, Majuro Atoll in the Marshall Islands received only 85% of the normal rainfall for the period (Presley, 2005). By April 1998, the Majuro Water and Sewer Company (MWSC), which relies primarily on rainwater catchment and to a less extent on groundwater, was only able to provide water to the island's 27,000 residents and businesses for about 10 hours every two weeks. Health officials reported more than 1,000 cases of dehydration, drought-related skin disease, and respiratory infections ("Marshall Islands drought assistance continues," 1998).

Because of human health concerns, large reverse-osmosis water-purification systems, capable of producing 473,174 liters (125,000 gallons) of freshwater per day from treated seawater, were brought to Majuro to help alleviate the water shortage. Concurrently, groundwater withdrawals from the freshwater lens in the Laura area of the atoll were increased from 378,541 liters (100,000 gallons) to a maximum of 1,082,627 liters (286,000 gallons) per day (Presley, 2005). During the drought, public concern arose about these increased groundwater withdrawals because of the potential impact of saltwater intrusion on taro, breadfruit, and banana crops. The US Geological Survey, in cooperation with the Republic of the Marshall Islands government and the Federal Emergency Management Agency, installed monitoring wells to determine the condition of the freshwater lens during the drought. Results indicated that saltwater intrusion had not affected crops despite the increase in groundwater withdrawals. The study demonstrated the importance of maintaining a groundwater monitoring program to (1) evaluate the status of the freshwater lens, (2) indicate a sustainable pumping rate that will protect the resource from saltwater intrusion, and (3) help local organizations such as the MWSC address public concerns (Presley, 2005).

This case study demonstrates the vulnerability of freshwater resources on atoll islands. Data from monitoring are needed to manage rainwater and groundwater resources conjunctively and increase the adaptive capacity of low islands to meet the challenges posed by climate variability and change. With no monitoring plan in place or funding to upgrade the groundwater pumps in Laura, the existing on-island adaptive capacity to respond to the drought was low, despite warnings received in advance.

Integrated management of rainwater and groundwater resources is critical for water

Case Study 2-1 Photo 1 Taro crops destroyed by saltwater inundation at Lukunoch Atoll, Chuuk State, Federated States of Micronesia. Giant swamp taro (*Cyrtosperma*) is a staple crop in Micronesia that requires a two- to three-year growing period from initial planting to harvest. It may take two years of normal rainfall to flush brackish water out of a taro patch, so there will be a five-year gap before the next harvest, assuming no more saltwater inundation takes place (Hezel, 2009). (Courtesy of John Quidachay, USDA Forest Service.)

security, especially on the less-developed atoll islands in the Republic of the Marshall Islands and Federated States of Micronesia (Hamlin & Takasaki, 1996). One way to help alleviate chronic water-supply shortages during droughts would be to develop groundwater resources for non-potable uses where feasible so that rainwater can be saved for drinking and cooking.

Although groundwater from shallow wells can be used to mitigate water shortages during droughts, rainwater catchment systems are the only source of freshwater when storm waves and uncommonly extreme high tides known as "king tides" inundate low-lying atoll islands, turning all the groundwater brackish. In December 2007 and again in 2008, several atoll islands in the Federated States of Micronesia were flooded by a series of high-sea/surf events. These saltwater floods had a significant impact on taro crops that are commonly cultivated in a depression near the center of the island. In December 2007, on the outer islands of Chuuk State, where 13,000 people or one-fourth of the state population resides, an estimated 90% of all taro crops were destroyed by saltwater inundation (Hezel, 2009).

FOCUS ON ADAPTATION

Case Study 2-2

Using climate forecasts to save money and protect human health

When we leave the house in the morning, we often check the local weather forecast and make some quick decisions: *Should I bring an umbrella? How about a sweater?* By assessing the risks and taking action, we are effectively mitigating our vulnerability to weather-related impacts. While most people do not think twice about weighing uncertain weather information and taking action based on their best estimate of risk, it has proven much more difficult for community members, policymakers, and natural resource managers to integrate climate forecasts into their decision-making processes. By definition, climate risks have longer-term consequences, which make them easier to ignore in the short term. Yet a landfill on the island of O'ahu in Hawai'i demonstrated that climate information can be used to make management decisions that save time, money, jobs, and the health of our communities and natural environment.

Each year, the Weather Forecast Office (WFO) in Honolulu uses national El Niño and La Niña outlooks from NOAA to create island-level forecasts for Hawai'i. In conjunction with the Pacific ENSO Applications Climate (PEAC) Center, the WFO uses television, radio, and print and electronic newsletters to inform policymakers, managers, and communities about the potential seasonal impacts of an El Niño or La Niña event. In October 2010, the Honolulu WFO gave its winter wet-season (October to April) briefing, indicating that due to a moderate-to-strong La Niña (Figure 2-17) developing in the Pacific, O'ahu could expect above-average winter rainfall.

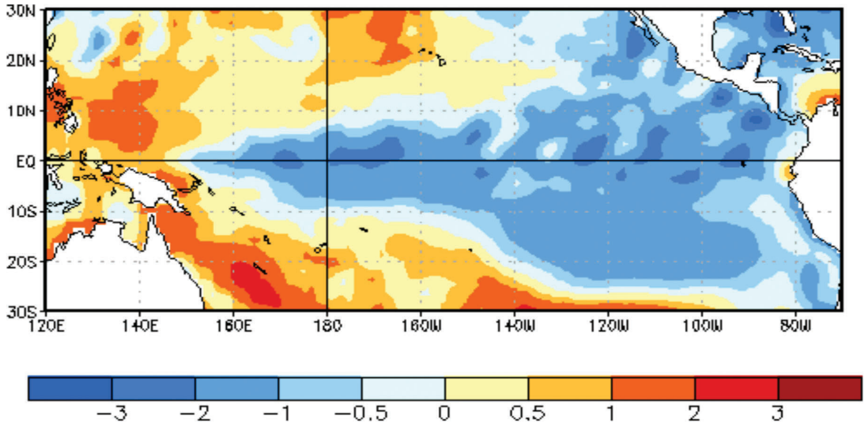


Figure 2-17 The NOAA Climate Prediction Center (CPC) released a seasonal ENSO outlook indicating La Niña conditions, or colder-than-average sea-surface temperatures in the equatorial Pacific Ocean. Here, in December 2010, the plume of cold (blue) water is visibly extending westward along the equator. (Courtesy of NOAA CPC, "December 2011 Sea-surface Temperatures.")

The vice-president of an O'ahu commercial landfill, PVT Land Company in Nanakuli, used this information, and his company immediately took steps to mitigate the climate risks. The company's managers decided to move quickly to upgrade infrastructure that would divert and hold large amounts of stormwater. By the end of November 2010, PVT had finished upgrading its storm drainage system and retention ponds.

The dry Nanakuli area usually receives a total of 254 to 356 mm (10 to 14 inches) of rain annually, but on January 13, 2011, the area received about 356 mm (10 inches) in a single storm. Other local landfills were not prepared to handle the intense rainfall and ended up closing down. They also released hazardous untreated water and waste onto local beaches. But due to their good use of climate forecasts, PVT Land Company was open for business the next day.

By remaining open, PVT estimates that they saved about $1 million in gross sales, potential damage to infrastructure, and lost salaries. This estimate does not include the additional financial impacts from the construction and trucking jobs across the island that would have had to slow down or stop had they not been able to properly dispose of their on-site debris, or the savings from avoiding potential litigation had the stormwater system failed.

This case demonstrates the actual and potential savings associated with taking an active role in making planning and management decisions based on the best available climate information, as well as the type of successful adaptations that can be accomplished when adaptive capacity in a region and institution is very high. It is often difficult to quantify long-term negative consequences that are associated with failing to act on or make a decision earlier in time; however, the PVT case provides an excellent shorter-term example with quantifiable benefits for policymakers, scientists, communities, and businesses who are willing to work together to make and act upon climate forecast–based decisions. The PVT landfill continues to use seasonal climate forecasts to guide their mid-range planning process and is interested to learn about what longer-term local climate projections can assist them in their goals of continuing a safe and efficient business.

For more information on the PEAC Center or to receive their free regional ENSO forecast newsletter, please visit: *http://www.prh.noaa.gov/peac/*

Case Study 2-2 Photo 1 The PVT Land Company (left) is O'ahu's only landfill for construction-site waste and receives over 200 truckloads of construction debris per day. If it was unable to receive waste, construction and trucking jobs on O'ahu would have to slow or cease. In making a fast decision using a seasonal climate forecast, PVT upgraded their stormwater drainage system and retention pond (right) to be able to accommodate increased volumes of stormwater. (Courtesy of Dr. Victoria Keener [left]; courtesy of Bill Lyon, TerraPac, LLC [right].)

FOCUS ON ADAPTATION

Case Study 2-3

Climate change likely to intensify freshwater disputes in Hawai'i

While the high islands of Hawai'i are wetter than much of the western United States, Hawai'i has a similar regional history of intense legal fights over water. Ongoing conflicts not only illustrate how sectors and players compete but also show how changes in the abundance and distribution of water caused by climate change may intensify these prolonged battles.

Contemporary conflicts over water allocation in Hawai'i have their origins in the mid-1800s, when King Kamehameha III created private property in land but continued to hold water as a public trust, setting the stage for conflict between emerging water-intensive agribusiness and traditional users. Today's battles take place under a legal framework that includes judicial precedent (including decisions made during the Hawaiian Kingdom) (Hawaiʻi Revised Statutes [HRS] 1-1); state constitutional provisions that reiterate the public trust in water and Native Hawaiian rights (Haw. Const. art. XI, § 1 & 7, art. XII §1-4 & 7); and the state's Water Code (HRS 174C). The State Commission on Water Resource Management attempts to balance public trust uses of water (including traditional and customary Hawaiian practices, the procreation of fish and wildlife, and the maintenance of ecological balance and scenic beauty) against a goal of maximizing beneficial uses (including agricultural, commercial, and industrial consumption).

The largest ongoing fight has been on the island of Oʻahu, where the Waiāhole Ditch system was developed in 1913–1916 to deliver water from the wet, windward Koʻolau Mountains to the dry, southern leeward plain for sugar cultivation. While originally designed to capture stream water, the construction of the delivery tunnels pierced large volcanic dike compartments (Figure 2-1), releasing stored groundwater and over time changing the underlying hydrology of windward streams (Takasaki & Mink, 1985). Beyond the immediate impact on ecosystems, this significantly disrupted nutrient flow into Kāneʻohe Bay, the largest estuarine system of the Pacific Islands (in re Water Use Permit Applications, 94 Haw. 97 P.3d 409 (2000)).

The current battle ignited in 1995 with the closure of the plantation using this water. Before the State Commission on Water Resource Management and later the Hawaiʻi Supreme Court, leeward interests (including groups in the agricultural, development, military, and tourism sectors) sought to maintain ditch flows, while conservationists, Native Hawaiians, and small riparian farmers sought to restore windward streams. The current allocation restores approximately one-half of the water to the streams of origin. The years of litigation have cost millions of dollars, and today, the case is on its third appeal to the Hawaiʻi Supreme Court.

The Hawaiʻi Supreme Court's decisions have affirmed a public trust in water and demand adherence to the precautionary principle in managing the trust. Decisions up to now, however, have not taken into account the decline in rainfall and base flow observed over the past 60 years (Oki, 2004) or effects from other threats to forested recharge areas.

An ongoing battle on Maui is even more intense than the Waiāhole fight because of concerns about groundwater available for the island's human population. Small riparian farmers and conservationists have sought regulation of groundwater withdrawals and restoration of streamflows from historic plantation diversions that were designed to capture 100% of base flows (Figure 2-18). This battle has pitted developers, agribusiness interests, and the county against small farmers, Native Hawaiians, and conservationists. It has been before the State Commission on Water Resource Management and is currently on appeal to the Hawaiʻi Supreme Court (Commission on Water Resource Management, 2010).

As on Oʻahu, rainfall and base flow on Maui show a statistically significant long-term decline (Figures 2-5, 2-8). Recent data (Giambelluca et al., 2011) suggest that this trend could continue, with profound consequences for the island's water resources.

On the leeward side of Hawaiʻi Island, an emerging dispute over the allocation of water focuses on the effects of water use on groundwater-dependent ecosystems. Water demand is being driven by significant resort, commercial, and residential development. According to the 2010 US Census, population in the North Kona and South Kohala areas

Figure 2-18 In Maui's ʻĪao Valley, conservationists and small farmers would like to restore historic streamflows away from plantation-era diversions that capture all base flow. Proponents of restoring historic flow levels would like to use the water for traditional cultural and agricultural practices and for restoring the habitat of native species. (Courtesy of Jonathan L. Scheuer.)

increased more than 30% in the past decade. With few streams on this part of the island, water needs must be met by groundwater. The underlying hydrology is poorly understood, however, and the state's calculation of sustainable yields depends on a simple mathematical model (Oki & Meyer, 2001). Water-planning documents that estimate consumption show demand likely to exceed the sustainable yield in most growth scenarios (Hawaiʻi County, 2010).

Important coastal resources with dual ecological and cultural significance depend on groundwater. These include anchialine pools (Figure 2-19), coral reefs, and Native Hawaiian fishponds. They may be significantly affected by increased groundwater withdrawals (Oki, 1999). Current work to model these systems and integrate new recharge and rainfall data may lower estimates of what withdrawal levels will be sustainable.

In these and other emerging situations, changing climate may well intensify water disputes that already tend to be the most difficult, unresolved public policy issues in the islands. While some policy tools (such as the Public Trust and the Precautionary Principle) may help resolve these conflicts, it is likely that disputes will multiply and intensify as demand for water increases, possibly in the face of diminishing supply.

Figure 2-19 Anchialine pools, such as the Kukiʻo Pools on Hawaiʻi Island, are unique environments found only in the coastal tropics and sub-tropics. The pools have no surface connection to the ocean yet can range from fresh to brackish. Anchialine pools are critical habitat for several rare and endemic species, such as *opaeʻula* red shrimp, snails, and insects. (©2010 Rosa Sey, "One of the Kukiʻo anchialine ponds," used under a Creative Commons Attribution-NonCommercial-NoDerivs license.)

Chapter 3

Sea Level and Coastal Inundation on Pacific Islands

COORDINATING LEAD AUTHORS*

John J. Marra (NOAA NCDC), Mark A. Merrifield (JIMAR, University of Hawaiʻi at Mānoa), William V. Sweet (NOAA COOPS)

CASE STUDY CONTRIBUTORS*

Dolan Eversole (Sea Grant, University of Hawaiʻi at Mānoa), Charles Fletcher (SOEST, University of Hawaiʻi at Mānoa), William V. Sweet (NOAA COOPS)

CONTRIBUTORS*

Amanda Amjadali (Australia BOM), Jérome Aucan (RDFrance), Pat Caldwell (NOAA NODC), Ed Carlson (NOAA NGS), Don Chambers (University of South Florida), Rashed Chowdhury (JIMAR, University of Hawaiʻi at Mānoa), Frank Colberg (Australia CSIRO), Ayesha Genz (UHSLC), John Hall (DOD SERDP), John Hunter (ACECRC), David Jay (Portland State University), Jens Kruger (SPC SOPAC), Mark Lander (University of Guam, WERI), Dough Marcy (NOAA CSC), Melissa Menendez (Environmental Hydraulics Institute, Universidad de Cantabria), Gary Mitchum (University of South Florida), Steve Nerem (University of Colorado), Doug Ramsay (New Zealand NIWA), Peter Ruggiero (Oregon State University), Giovanni Sella (NOAA NGS), Thomas Smith (USACE PRO), Curt Storlazzi (USGS PCMSC), Claudia Tebaldi (Climate Central), Keith Thompson (Dalhousie University)

*LISTED IN ALPHABETICAL ORDER

This Chapter should be cited as:
Marra, J. J., Merrifield, M. A., & Sweet, W. V. (2012). Sea Level and Coastal Inundation on Pacific Islands. In V. W. Keener, J. J. Marra, M. L. Finucane, D. Spooner, & M. H. Smith (Eds.), *Climate Change and Pacific Islands: Indicators and Impacts*. Report for the 2012 Pacific Islands Regional Climate Assessment (PIRCA). Washington, DC: Island Press.

Island regions face a wide range of challenges associated with sea-level rise (SLR). High mean water levels and the possibility of more frequent extreme water level events in a changing climate threaten coastal structures and property, groundwater reservoirs, harbor operations, waste water systems, sandy beaches, coral reef ecosystems, and other social and economic concerns. Low islands are especially vulnerable given their limited elevation above present-day sea level. Global SLR is a concern for all island regions, although short- to medium-term impacts (several decades) will vary with location depending on how natural sea-level variability combines with modest increases of mean levels. Over longer time scales (end of the century), projected SLR is likely to exceed important height thresholds, and together with possible climate-related changes in storm patterns and regional winds, may lead to chronic high water levels along island coasts.

In this section, we summarize the current understanding of global sea-level rise and recent regional deviations from the global rate for the Pacific Ocean. Factors that contribute to high-water-level events are described, and their relative importance for different islands within the region is discussed. We consider some of the challenges involved in projecting sea-level change and summarize outlooks for mean and extreme sea-level change for the Central North Pacific (Hawai'i); Western North Pacific (Guam, Republic of Palau (RP), Federated States of Micronesia (FSM), Commonwealth of the Northern Marianas Islands (CNMI), Republic of the Marshall Islands (RMI)); and Central South Pacific (American Samoa).

Overview

Elevated water levels result from the complex interplay of a spectrum of oceanic, atmospheric, and cryospheric processes (Figure 3-1). At one end of the spectrum are variations in elevation associated with the passage of surface gravity waves. These short-period (seconds to minutes) variations are superimposed upon longer-period (hourly to daily) variations in elevation attributable to phenomena such as tides and storm-induced surge. These elevation changes, in turn, rest upon other effects primarily related to variations in wind strength and ocean circulation that affect elevations at even longer time scales (weeks to decades). At the other end of the spectrum are isostatic and cryospheric variations (over decades to millennia). The challenge is to understand how the phenomena that manifest across this continuum interact to determine water levels at specific places and times (Marra et al., 2007).

Averaged over the global ocean, sea level currently is rising at a relatively slow and subtle rate (tens of centimeters/inches per century) compared to fluctuations attributable to sea-level variability. Global sea level rises because of an increase in the volume of ocean water due to changes in both density and mass (Figure 3-2), which are both affected by global warming. Heating of the ocean surface causes the water to become less dense and to expand and rise, whereas heating and melting of glaciers and ice sheets transfers water mass from the land to the ocean.

In addition to ocean changes, sea level relative to land can also change due to vertical movement of the land itself, which can occur at rates comparable to global SLR. A primary cause for vertical land motion is the glacial isostatic adjustment (GIA) of the continents in response to melting ice. These signals appear at high latitudes as an apparent

Figure 3-1 Factors affecting extreme water levels in the Pacific Islands. In the Pacific Islands, extreme water levels primarily result from a combination of global and regional changes in mean sea level due to the addition of mass and density changes driven by processes operating over centuries to millennia; ENSO and other modes of natural variability that control regional to local mean sea level over decades to months; tropical and extra-tropical storms, and swell from distant storms that manifests as events lasting hours to seconds; unusually high tides; and regional to local vertical land motion. (Figure courtesy of John Marra.)

fall in sea level as the continents rebound under a reduced ice mass load. Other factors affecting vertical land motion include groundwater or oil extraction, local tectonic activity, and island subsidence near hot spot formation regions. Assessments of sea-level rise impacts at any location require consideration of vertical land motion. For example, the high apparent rate of SLR at Torres Islands, Vanuatu, has been attributed to subsidence of the islands, primarily due to episodic earthquakes (Ballu et al., 2011).

Superimposed on the global SLR signal are regional sea-level variations (Figure 3-3). The amplitude of these sea-level variations is generally on the order of tens of centimeters (less than a foot) on a year-to year time scale, and on the order of centimeters (an inch) on a decade-to-decade time scale. Although these height variations generally are weak, they can strongly influence sea-level trend estimates on multi-year to multidecadal time scales. The most energetic regional sea-level variations in the Pacific Islands region are associated with the El Niño Southern Oscillation (ENSO) (e.g., Wyrtki, 1975; Becker et al., 2012). During La Niña events, enhanced trade winds cause Pacific water levels near the equator to rise in the west and to fall in the east. During El Niños, the relaxation of the trade winds causes the pattern to reverse. Energetic ENSO events in the tropical Pacific can cause sea levels to rise by 10 to 20 centimeters (6 to 12 inches) above mean conditions.

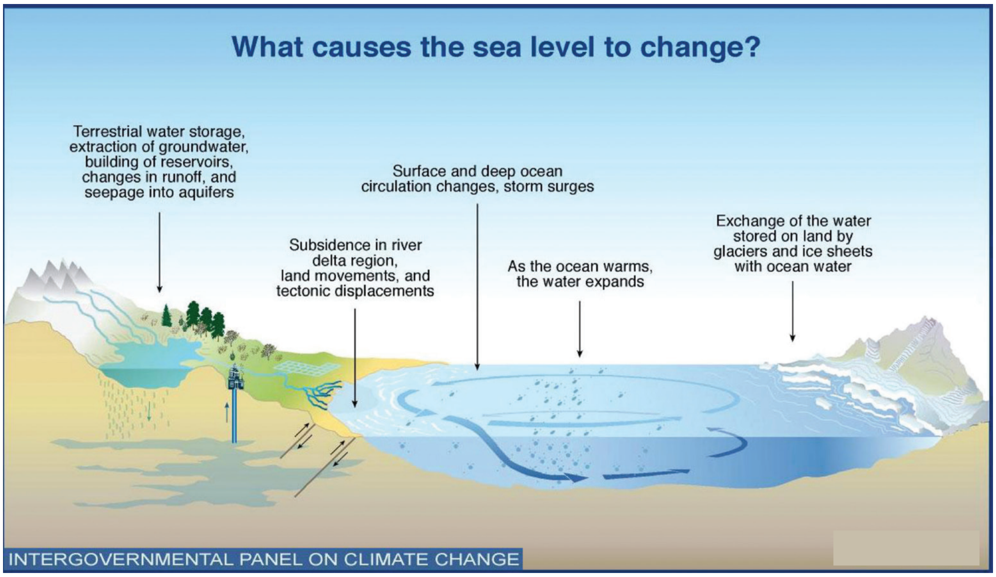


Figure 3-2 Causes of sea-level change. (From IPCC, 2001.)

The most damaging inundation events are associated with storm surges caused by tropical and extra-tropical storms. The passage of a low-pressure system can cause sea level to rise a centimeter (roughly half an inch) for every millibar drop in atmospheric pressure (the inverse barometer effect), and storm winds can cause a surge of coastal water levels of tens of centimeters (inches) to meters (feet). The impact of storm-driven waves is twofold: breaking waves cause water levels to rise at the shoreline in some cases by 20% to 30% of the breaking-wave height, and energetic wave motions can lead to inundation and flooding. Wind and wave impacts vary with local topography, particularly with the presence of coral reefs, which significantly reduce wave energy. Flooding and erosion impacts will also vary with the elevation of the groundwater table and rates of precipitation.

Swell waves from distant storms pose a significant inundation risk. Breaking waves lead to high water levels at the shore, known as wave setup. In addition, swell waves and lower-frequency waves tied to wave groups can cause variable runup at the shoreline. Coral reefs are the primary defense against wave-driven inundation, in that they cause significant swell wave dissipation due to breaking and frictional decay compared to exposed sand beaches. Setup and low frequency runup are less affected by the presence of reefs than ocean swell.

Historic and current trends

Global

Since the early 1990s, the rate of globally averaged sea-level rise has been estimated to be 3.4 ± 0.4 mm (0.134 ± 0.016 inches) per year based on satellite altimeter measurements (Nerem et al., 2010). This is twice the estimated rate for the 20th century as a whole based on tide-gauge reconstructions (reviewed by Bindoff et al., 2007). A statistically

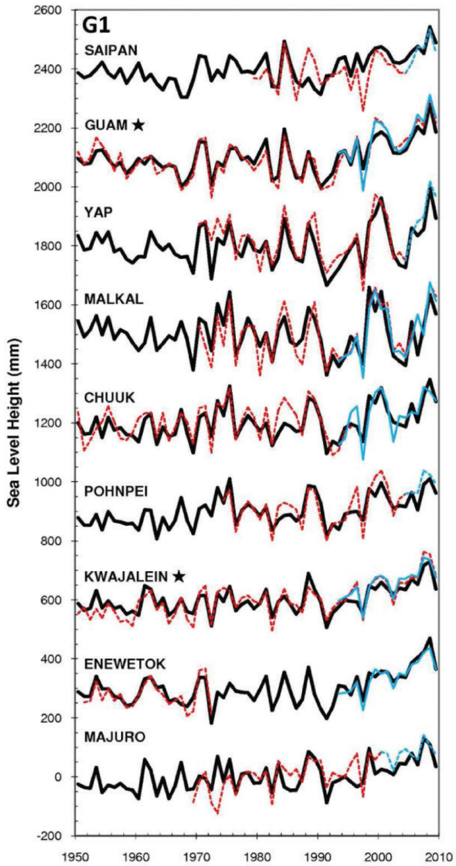


Figure 3-3 Sea-level time series (red) at Pacific Island tide-gauge sites, including reconstructed time series (black) and altimeter sea levels (blue). Note high interannual variability and the recent upward trend since the mid-1990s. (From Becker et al. [2012] by permission of Elsevier.)

significant acceleration in the global trend has been reported, largely reflecting an increase between the 19th and 20th centuries (Church and White, 2006; Jevrejeva et al., 2008; Church et al., 2011). A related issue is whether the recent altimeter trend represents an acceleration compared to tide-gauge estimates for the 20th century. Global sea-level reconstructions using tide-gauge data show trends over 10- to 15-year time spans that are comparable to the present altimeter rate, suggesting that multidecadal fluctuations in global sea level are important and that the current rate may represent a peak in these fluctuations (Church et al., 2004; Holgate, 2007). On the other hand, the recent high trend is partially explained by an estimated increase in the amount of freshwater input to the ocean due to melting glaciers and ice sheets (Church et al., 2011), which is less likely to represent a fluctuating signal on these time scales. In addition, Merrifield et al. (2009) find that the recent global trend increase appears to stand alone during the second half of the 20th century based on a spatially distributed set of tide-gauge stations. The issue of trends versus decadal variations in global sea level is under investigation.

Regional

Regional sea-level trends may differ significantly from the globally averaged rate over multi-year to multidecadal time scales (Stammer et al., 2012). For example, for 1993–2010,

Box 3-1

How do you measure sea level?

Sea level, for most applications, can be considered the long-term average of the ocean's surface. It is often referred to as local or global, though in either case it is rarely at its mean level. Forces are constantly causing change, from the rhythmic influence of the tides to long-term climatic changes associated with sea-level rise (SLR). Global sea level is rising on average, though not uniformly, mainly from land-ice melt and thermal expansion of the world's oceans. Since 1992, satellite altimeters have provided a detailed view of where and how fast global SLR has been occurring (*http://sealevel.jpl.nasa.gov*). Before this time, a global network of tide gauges (see below) and a few other techniques were used to approximate global SLR. Altimeters measure the cumulative response from all inputs and make ~10-day repeat observations of the world's ocean surface from a fixed-space reference frame. Another space-based platform, the Gravity Recovery and Climate Experiment (GRACE; *http://grace.jpl.nasa.gov*), can detect small changes in the Earth's gravity field as land ice melts, adding to the SLR signal measured by altimeters. Throughout the oceans, the Argo network of profiling floats (*http://www.argo.ucsd.edu*) tracks the other major factor causing global SLR—thermal expansion—by measuring changes in the ocean's temperature (and salinity).

Most relevant to human societies living along the continental margins are the relative changes to local sea level occurring at the land-ocean interface. Relative SLR is measured by tide gauges, which record vertical land motion as well as locally realized changes in global SLR (e.g., dynamic changes). Tide gauges are of critical importance as they capture the coastal response—from tides to SLR—as well as extreme events. NOAA operates a vast array (> 200) of gauges throughout the US (many of which have been in operation for 100+ years) as a part of the NOAA's National Water Level Observation Network (NWLON). NWLON gauges track local SLR and provide a connection between mean sea level (MSL) and geodetic reference frames (e.g., GPS or surveyed land elevations) via their benchmark network. A subset of NWLON gauges comprises the US contribution to the international Global Sea Level Observing System (GLOSS) Global Core Network (GCN), the primary global observing system for in situ sea level. The University of Hawai'i Sea Level Center (UHSLC) is also a key contributor to GLOSS. In addition to maintaining nearly 80 gauges worldwide, the UHSLC reviews and archives tide-gauge observations from nearly 500 gauges and 70 international agencies. The Joint Archive for Sea Level (JASL) research-quality dataset, managed and hosted at UHSLC, is the premier global sea-level data set.

the standard deviation of regional trends based on satellite altimetry is as large as the global mean trend, and trend deviations from the mean are particularly pronounced in the Pacific basin (Figure 3-4). Regional trend variations on these time scales generally are attributed to changes in prevailing wind patterns due to natural climate variability. Examples of wind-driven changes in regional sea level that are particularly relevant to the Pacific Islands region include ENSO events on interannual time scales (e.g., Wyrtki, 1975; Chowdhury et al., 2010; Becker et al., 2012) and the Pacific Decadal Oscillation (PDO) on decadal to multidecadal time scales (e.g., Feng et al., 2004; Di Lorenzo et al., 2010; Bromirski et al., 2011; Merrifield et al., 2012).

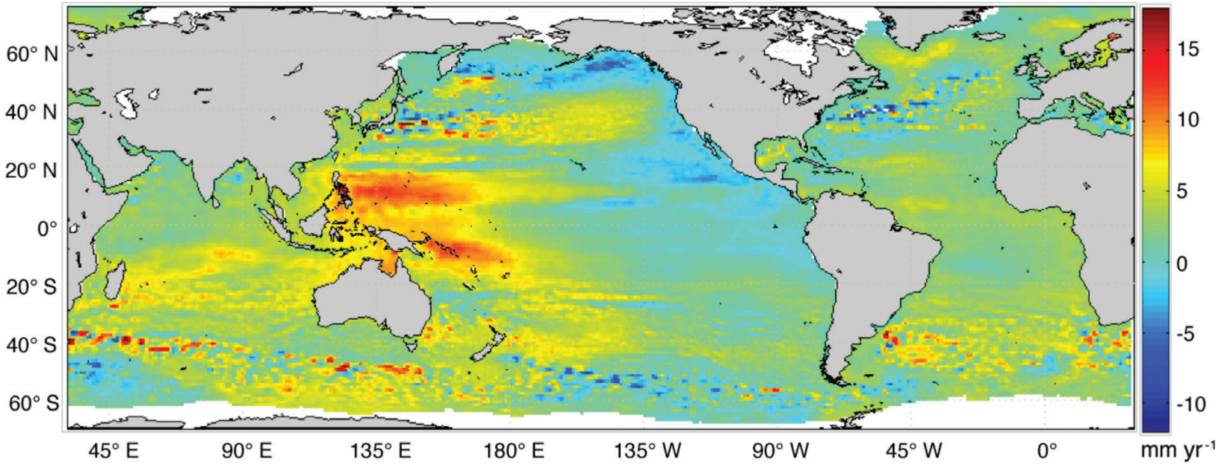


Figure 3-4 Sea-level trend for 1993–2010 from Aviso altimeter product, produced by Ssalto/Duacs with support from the Centre National d'Etudes Spatiales. (From Merrifield [2011] by permission of American Meteorological Society.)

The highest rates of regional SLR during 1993–2010 have occurred in the western tropical Pacific (Cazenave & Llovel, 2010; Nerem et al., 2010; Timmermann et al., 2010) (Figure 3-4). A multidecadal increase in the strength of the trades since the early 1990s accounts for the high sea-level trends in the western tropical Pacific that have not been observed since tide-gauge measurements began in the 1940s (Feng et al., 2010; Merrifield, 2011; Merrifield & Maltrud, 2011; McGregor et al., 2012). Becker et al. (2012) show that a reconstruction of regional sea level in the western tropical Pacific that incorporates the global mean rise, low-frequency regional variations, and ground motion has created a significant total sea-level change, particularly at Funafuti Atoll in Tuvalu. In contrast, an earlier sea-level reconstruction for 1950–2001 shows rates in the western tropical Pacific that are below the global average (Church et al., 2006). The current high sea-level rise rates in the western tropical Pacific have been linked to trade wind fluctuations associated with the PDO and low-frequency components of the Southern Oscillation Index (SOI) (Feng et al., 2010; Merrifield et al., 2012), suggesting that the high regional trend is due to natural climate variability. The recent rise reflects weak (order of centimeters) multidecadal fluctuations in water level that track the PDO/SOI (Figure 3-5)—that is, the current rates are not expected to persist over time, and the net result of the regional trend will be a few centimeters (inches) of sea-level change in the region before falling once the trade winds begin to weaken. In addition to the impact on sea level, the PDO/SOI may be associated with recent trends in tropical storm activity and rainfall observed in the western Pacific (Maue, 2011). Further research is required to evaluate the ongoing impacts of decadal trade wind variations on water levels, rainfall, and storminess broadly across the entire region.

Vertical land motion contributes to relative sea-level trends at islands (e.g., Caccamise et al., 2005; Wöppelmann et al., 2007; Becker et al., 2012). Becker et al. (2012) provide an assessment of vertical land motion at islands in the western tropical Pacific

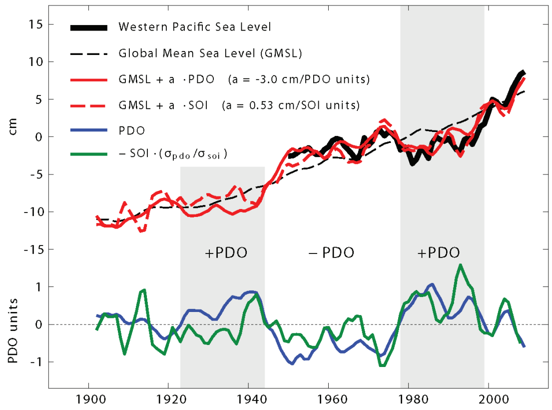


Figure 3-5 Western Pacific sea level (black) compared to reconstructions based on the PDO (red) and the SOI (red dash) with the Church and White (2011) global mean sea level included (black dash). The PDO index (blue) and scaled SOI (green) are shown for comparison. (©2012 American Geophysical Union. Reproduced/modified from Merrifield et al. [2012] by permission of American Geophysical Union.)

based on global positioning system (GPS) solutions. Islands with negative rates (i.e., land is subsiding, which contributes to positive relative sea-level trends) include Pohnpei (–0.6 mm:–0.024 inches per year) and Pago Pago (–0.4 mm:–0.016 inches per year). The land motion is positive at Guam (+0.4 mm:+0.016 inches per year) and at Honolulu (+0.46 mm:+0.018 inches per year) (Wöppelmann et al., 2007), with variations along the Hawaiian Islands chain (Caccamise et al., 2005). The rates represent the movements at a single point at each island, and uncertainties on these rates are high given the short record lengths available. Additional measurements are needed to assess vertical land motion at Pacific Islands.

Extreme sea-level events

The main causes for extreme sea-level events in the region include tropical and extratropical storms, unusually high tides sometimes referred to as king tides, ENSO, ocean mesoscale variability, and swell events from distant storms. Statistical assessments of extreme sea levels in the region and elsewhere have relied primarily on tide-gauge observations (reviewed by Woodworth et al., 2011). Because tide-gauge stations generally are located in places that do not experience wave-driven setup, although stations in exposed atoll lagoons (e.g., Midway) are a notable exception (Callaghan et al., 2006; Aucan et al., 2012), the influence of distant swell generally is not considered in tide gauge–based assessments. Extreme sea-level trends in tide-gauge records tend to match trends in local mean sea level (Woodworth & Blackman, 2004; Menéndez & Woodworth, 2010). This suggests that the causes of extreme sea levels at tide gauges have not changed over the tide-gauge record, and that changes in extreme levels are due to changes in mean levels. Thus, increases in mean levels are expected to result in an increased frequency in extreme events (Firing & Merrifield, 2004).

The range of tidal and nontidal residual extremes has been estimated for a global set of tide gauges (Menéndez & Woodworth, 2010). Stations can be grouped regionally into those where high tides dictate extremes (e.g., RMI), where the combination of high tides and the nontidal residual is important (e.g., main Hawaiian Islands), and where nontidal residual events are the primary cause of extreme levels independent of the tide (e.g., Guam, CNMI) (Merrifield et al., 2012) (Figure 3-6). The phasing of extremes over

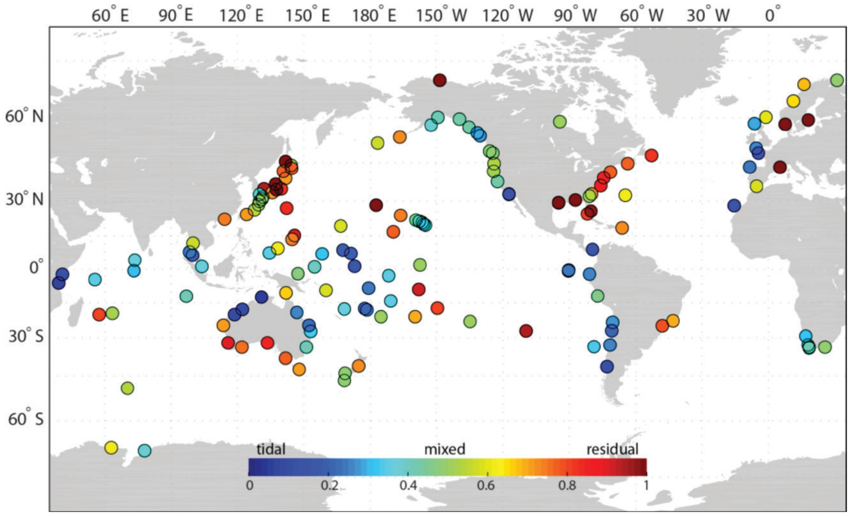


Figure 3-6 The ratio of mean nontidal residual to mean extreme amplitude for annual maxima. (©2012 American Geophysical Union. Reproduced/modified from Merrifield et al. [2012] by permission of American Geophysical Union.)

the course of the year has also been examined and related to storm versus tidal forces. In regions where the tide determines extreme levels, highest levels will be influenced by astronomical cycles, such as the equinoctial spring tides, the quasi 4.4-year perigean cycle, and the 18.6-year nodal cycle (Menéndez & Woodworth, 2010).

In the equatorial Pacific, interannual variations in extreme events are pronounced in regions affected by ENSO (Menéndez & Woodworth, 2010; Chowdhury et al., 2010). In the western tropical Pacific, peak La Niña events can lead to 10 to 20 cm (~1 foot) sea-level anomalies (Figure 3-3). ENSO sea-level variations are also pronounced along the eastern boundary of the Pacific (e.g., Cayan et al., 2008), and in the western sub-tropics (Kawabe, 2000). Other than ENSO, interannual to interdecadal sea-level fluctuations are associated with modest changes in sea level, with peak events typically < 10 cm (~4 inches)—for example, Honolulu sea level (Firing et al., 2004). Fluctuations of this magnitude are a concern to the extent that they contribute to high tide events. The same holds true for intra-annual sea-level variations associated with ocean processes, such as mesoscale eddy events—for example, 10 to 15 cm (~4 to 6 inches) at Wake Island (Mitchum, 1995) and at Honolulu (Firing & Merrifield, 2004).

Extreme island surge events result from wind, wave, and atmospheric forces associated with tropical storms. Guam and CNMI are particularly vulnerable, lying in a region of frequent and energetic typhoons (Figure 3-7). Hawaiʻi and American Samoa experience fewer direct encounters with tropical storms, although when storms do occur, the impacts can be profound (e.g., Fletcher et al., 1995; Cheung et al., 2003). A key issue for climate change impacts on sea level is whether storm tracks and intensities are expected to change under future warming scenarios.

Distant storms also influence island sea levels through the generation and propagation of ocean waves. On island shorelines, the increase in water level caused by breaking waves (i.e., wave setup) can be on the order of 35% of the offshore breaking wave height, even in the presence of fringing reefs (Vetter et al., 2010). For most island shorelines in the Pacific, wave runup represents the most prevalent nontidal sea-level anomaly, and

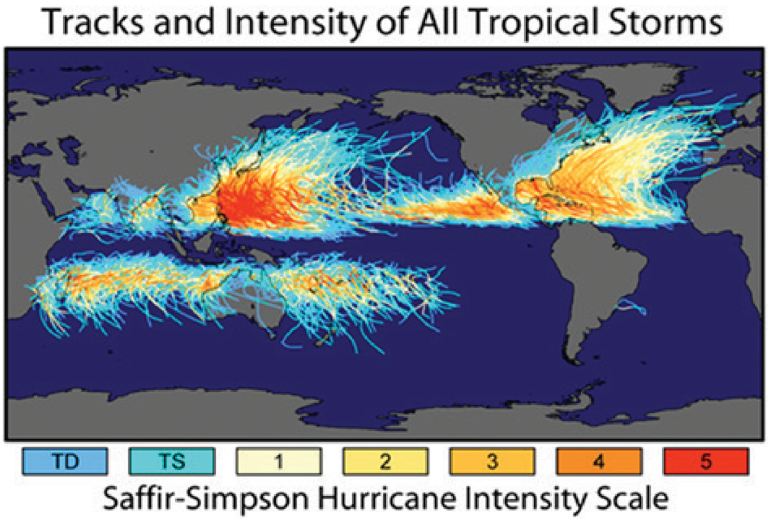


Figure 3-7 Map of cumulative tropical cyclone tracks and intensity. (Image by Robert A. Rohde, Global Warming Art. Courtesy of NASA Earth Observatory.)

potentially the most dangerous threat in terms of coastal inundation. For example, an unusual low pressure system in December 2008 near Wake Island led to the generation of energetic northeasterly (southwestward) swell that caused significant flooding at RMI and other western Pacific Island groups (Ford et al., 2012). Coastal flooding on the north shore of O'ahu, Hawai'i, tends to occur when wave-driven runup and high tides coincide (Caldwell et al., 2009). Offshore coral reef platforms significantly impact the amount of incident wave energy that contributes to coastal runup along island shorelines (Péquignet et al., 2011).

Given that long records of wave height generally are unavailable to evaluate wave climate changes for the Pacific Islands region on the whole, along with other considerations including the upward growth rate of the reef crest, it is difficult to assess climate-related changes in the tropical Pacific Island wave climatologies and hence in wave-driven water-level extremes (Young et al., 2011; Seneviratne et al., 2012). Using 23 years of satellite altimeter measurements to investigate global changes in oceanic wind speed and wave height, Young et al. (2011) found that there has been no statistically significant trend for mean monthly values, but for extreme conditions there is a statistically significant trend of increasing wave height at high latitudes and more neutral conditions in equatorial regions. Based on the analysis of buoy and voluntary observing-ship data, positive trends in wave height in the eastern North Pacific over the past several decades have been reported (Allan & Komar, 2006; Menéndez et al., 2008; Ruggiero et al., 2010; Seneviratne et al., 2012). A recent study by Gemmrich et al. (2011) has raised doubts about the significance of these results. Wave-driven setup within the Midway Atoll in the Hawaiian Islands chain captured in tide-gauge observations indicates that the number of storm wave events has increased significantly over the past 50 years, associated with variability of the Pacific Decadal Oscillation (PDO) index rather than a long-term trend (Aucan et al., 2012). Analysis of wave buoy and satellite altimeter data for trends in wave heights in the South Pacific has yielded mixed results (Hemer et al., 2010). Several studies show a strong correlation of wave height with natural modes of variability, in particular ENSO (Allan & Komar, 2006; Sasaki & Toshiyuki, 2007; Hemer et al., 2010; Seneviratne et al., 2012), yet the significance of interannual and decadal variations in wave properties remains to be fully evaluated.

The relative importance of the various factors causing extreme sea level in Pacific Island tide-gauge records has been quantified as part of the Pacific Storms Climatology Project (Kruk et al., 2012). Annual climatologies of extreme events observed in individual tide-gauge records have been constructed and separated into tidal, seasonal, and nontidal residual contributions, and are compared with the five largest observed extremes on record (Figure 3-8). The average daily extremes (black lines) are primarily associated with peak tides (blue lines) at Pago Pago. Seasonal (green lines) and nontidal residuals (red lines) contribute noticeably at Honolulu and Guam. The observed peak extremes (colored circles) tend to be marginally above the average extremes at Honolulu and Pago Pago, indicating that a combination of tides and moderate-amplitude nontidal residuals results in peak extreme events at these locations (e.g., a mesoscale eddy combined with a high spring tide; Firing & Merrifield, 2004). At Guam, the peak extremes are significantly above annual climatologies, indicating that energetic typhoon surge events set the highest inundation levels at these sites. Thus, not only can stations be grouped regionally into those where high tides dictate extremes, where the combination of high tides and the nontidal residual is important, and where nontidal residual events are the primary cause of extreme levels, but they also can be grouped by the combination of processes that contribute to the nontidal residual (e.g., tropical and extra-tropical storms, ocean mesoscale variability, and swell events from distant storms).

Climate projections and sea level

Based on climate model predictions for various greenhouse gas emission scenarios, the IPCC AR4 report estimates an 18 to 59 cm (~6 to 24 inch) rise in global sea level by 2100 (Meehl et al., 2007). These projections did not include contributions due to changes in the dynamics of ice-sheet discharge (which is less well understood and likely to be an increasing factor, particularly if greenhouse gas emissions are not reduced). Instead, IPCC AR4 provided an estimated rise in the upper ranges of the emission scenario projections that would be expected with “scaled-up ice sheet discharge” if contributions to sea-level rise were to grow linearly with global temperature change for each emission scenario. This was estimated within the IPCC AR4 as varying from an additional 9 to 17 cm (~4 to 7 inches) but was rounded up in the IPCC (2007) Synthesis Report to an additional 0.1 to 0.2 m (4 to 8 inch) rise. It was also clearly stated that larger contributions from the Greenland and West Antarctic ice sheets over this century could not be ruled out. Sea-level projections have also been made subsequent to AR4 using “semi-empirical models.” These models are based on statistical relationships between observed SLR and global temperature, coupled with projections of future global temperature. These models yield higher estimates of global SLR, ranging from roughly 1 to 1.5 m (~3 to 5 feet) by 2100 (e.g., Grinsted et al., 2010; Rahmstorf, 2007; Vermeer & Rahmstorf, 2009), than the AR4. Currently, there is an insufficient understanding for why semi-empirical models yield higher values than estimates based on climate models.

Figure 3-9a highlights recent studies chosen to formulate likely global sea-level change scenarios in order to provide broad-scale planning guidance for the US National Climate Assessment (NCA) process. “High,” “Intermediate,” and “Low” scenarios were

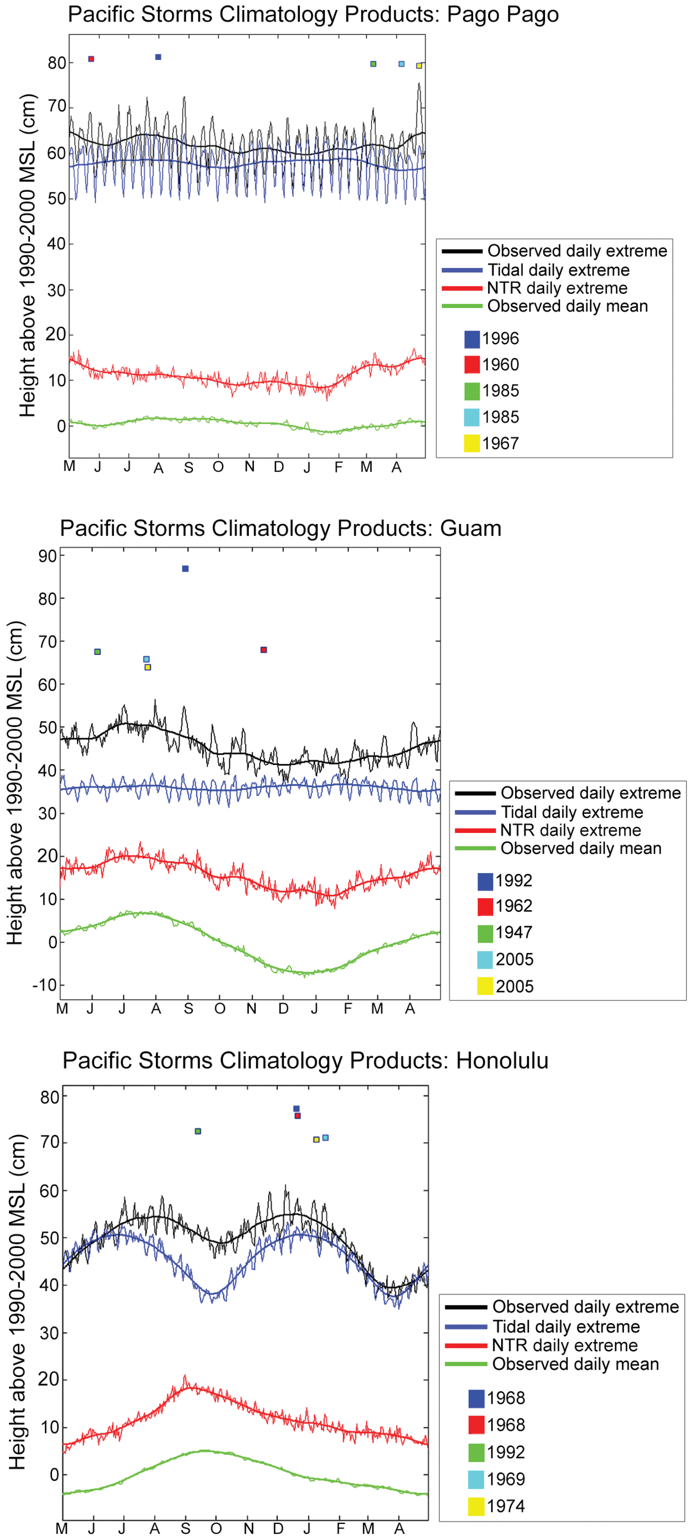


Figure 3-8 Extreme climatologies from tide gauges for each day of the year at selected tide stations in the Pacific (black, darker line is smoothed). The contribution to the extreme levels from the tides (blue), seasonal (green), and nontidal residual (red) are depicted. The five largest extreme events on record are also shown. Long-term linear trends in time series have been removed. Note how in Pago Pago (top), extremes are governed by the seasonal tidal signal. In contrast, in Guam (middle), it is the seasonal occurrence of tropical cyclones that dominates extremes. In Honolulu (bottom), there is both a tidal and a storm component in the signal. (From NOAA NCDC at *http://www.pacificstormsclimatology.org/*.)

established (Figure 3-9b). The NCA Low scenario (0.2m:0.66 feet) is based on linear extrapolation of the historic rate of global SLR over the 20th century (1.7 ± 0.2 mm:0.067 ± 0.008 inches per year; Church & White, 2011). The High (2m:6.56 feet) and Intermediate 1 (1.2m:3.94 feet) and 2 (0.5m:1.64 feet) scenarios represent future (by 2100) accelerations in global mean sea level (Figure 3-9b). These approaches are similar to those adopted by the National Research Council (1987) and the US Army Corps of Engineers (2011), which for simplicity initiate at the mid-point (1992) of the 1983–2001 National Tidal Datum Epoch (NTDE) currently in use by NOAA's National Ocean Service. There is no evidence, however, to assume that global SLR will evolve in this type of gradually changing manner. In addition, the skill of projections based upon semi-empirical methods is a topic of active debate, given the underlying assumptions inherent in extrapolating regression-based results to future scenarios.

Climate-related shifts in sea level are also predicted to occur in the future on a regional scale. Contributions to regional sea-level deviations from the global mean include gravitational changes associated with melting land ice, changes in GIA, and shifts in ocean dynamics (as an example, Figure 3-10). For the Pacific Islands region, the first

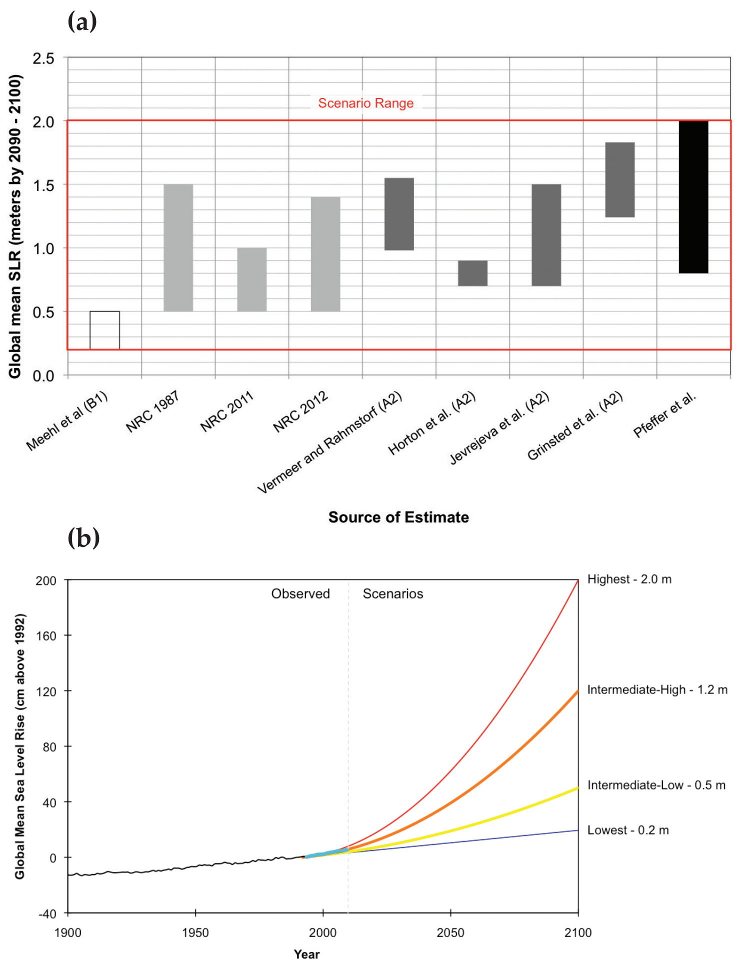


Figure 3-9 (a) End-of-century (~2090–2100) estimates for global mean sea level rise in meters. Meehl et al. (2007) is based on climate model projections for the IPCC and outlined in black. NRC (1987, 2011, and 2012) is based on synthesis of the scientific literature and shown in light gray. Vermeer and Rahmstorf (2009), Horton et al. (2008), Jevrejeva et al. (2010), Grinsted et al. (2009) are based on semi-empirical approaches and shown in dark gray. Pfeffer et al. (2008) is a calculation of the maximum possible contribution from ice sheet loss and glacial melting and shown in black. (b) Global mean sea level rise scenarios developed for the 2013 NCA. Present mean sea level (MSL) for the US coasts is determined from the National Tidal Datum Epoch (NTDE) provided by NOAA. The NTDE is calculated using tide gage observations from 1983–2001 and 1992, the mid-point of the NTDE, is chosen as a starting point. (From Parris et al., in press).

two effects are not expected to lead to strong spatial variations (e.g., Riva et al., 2010; Slangen et al., 2011; Australian Bureau of Meterology & CSIRO, 2011). Climate model simulations do indicate changes in ocean circulation and regional sea level (Stammer et al., 2012); but, as in the case of ENSO prediction, there is not a high level of confidence in these estimates at this stage.

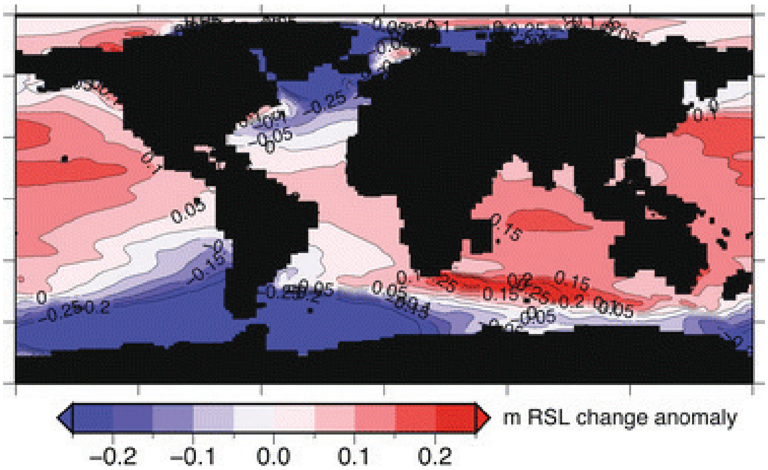


Figure 3-10 Local relative sea-level (RSL) change anomaly with respect to global mean change estimates (1.02 m:3.35 feet) between 1980–1999 and 2090–2099 based on an ensemble of coupled climate model simulations for the IPCC A1B emission scenario (IPCC, 2007) with an adapted ice-sheet contribution of 0.22 m (0.72 feet) for Greenland and 0.41 m (1.35) from Antarctica. (From Slangen et al., 2011.)

There are conflicting assessments as to how the tropical Pacific atmospheric circulation will respond in the future to climate change, so there is low confidence in the prediction of future wind patterns and their influence on regional sea level. Many modeling studies conclude that there will be a tendency toward a more El Niño–like background state in response to global warming (e.g., Vecchi & Soden, 2007; Yu & Zwiers, 2010), and a weakening of the Walker circulation over the 20th century has been attributed to anthropogenic forcing (Vecchi et al., 2006). Timmermann et al. (2010) use climate model projections to identify a water-level change in the southern tropical Pacific associated with increased trade wind speeds. Recent trends in the Indo-Pacific point to an enhanced La Niña state (e.g., Chen et al., 2002; Yu & Weller, 2007; Li & Ren, 2011; Feng et al., 2010) as well as modifications to classical El Niño patterns (Ashok & Yamagata, 2009; Kug et al., 2009). The separation of intrinsic climate variations, as these recent trends likely represent, from anthropogenic forcing represents a key area for future research.

Recent assessments of future extreme conditions generally place low confidence on region-specific projections of future storminess (Seneviratne et al., 2012).

Future wave conditions are difficult to project with confidence given the uncertainties regarding future storm conditions; however, progress has been made in the development of dynamical and statistical wave models. An intercomparison of global wave model projections using different approaches for simulating storm forcing based on CMIP3 projections and for different emission scenarios (SRES A1B: Mori et al. [2010], Semedo et al. [2012], Fan et al. [2012]; SRES A2: Hemer et al. [2012a]) has been performed by Hemer et al. (2012b). For the Pacific Islands region, the multi-model ensemble for the late 21st century indicates an increase in annual mean significant wave heights in the southern tropical Pacific associated with a strengthening of the trades, with most other areas of the Pacific showing a decrease. Similar findings are obtained using statistical models (Wang & Swail, 2006). Wind speeds are projected to increase over the southern Pacific, leading to increases in mean wave period and a shift toward a more southerly wave direction across the Pacific Islands region as austral winter swell propagates northward into the Pacific basin.

Whether or not future storm patterns will change appreciably over the next century does not diminish the impact that rising mean water levels will have on extreme events at Pacific Island regions. Hunter (2012), focusing on Australian sea-level stations, estimated that an increase of 10 cm (about 4 inches) in mean water level generally corresponds to a threefold increase in the frequency of extreme events on average. Thus, an increase of 20 cm (about 8 inches) will mean that what is currently the 100-year event will become the 10-year event. Enhanced storm impacts may add to these changes.

Impacts

Island regions face a wide range of impacts due to increased mean water levels and the possibility of more frequent extreme inundation events. These phenomena, manifest principally as increased flooding and erosion, threaten both natural and built environments. A key consideration with respect to the potential impacts of increased flooding and erosion is the inherent differences between high versus low islands, and their corresponding differences in both social and ecosystems diversity.

Low islands

Low islands are especially vulnerable to increasing mean water levels. Over the near to mid-term (next 25 to 50 years), they will be subject to increasing frequency and intensity of extreme events as mean water levels increase over time and as local storm impacts perhaps increase. This will result in a cascade of impacts that will increase the pressures on, and threats to, social and ecosystem sustainability in the Pacific Islands region (Storlazzi et al., 2011).

Their low elevation suggests that critical public facilities and infrastructure (e.g., roads, bridges, runways, water and waste water systems, and so forth) as well as private commercial and residential property will increasingly experience damage due to coastal flooding during extreme events. Beyond problems that already exist unrelated to climate change, freshwater resources will be a particular concern. On islands where there is groundwater, the lens is often small, shallow, and thus readily susceptible to thinning or loss due to intrusion of saltwater from the ocean during storms. Agricultural activity will be affected correspondingly—not only will sea-level rise decrease the land area available for farming (Easterling et al., 2007), but episodic inundation will increase the salinity of groundwater resources. Secondary effects include the fouling of sanitary systems. Taken together, these impacts will make human habitation of low islands increasingly untenable.

Long before islands are submerged as a result of SLR, coastal and nearshore environments (sandy beaches, shallow coral reefs, seagrass beds, intertidal flats, and mangrove forests) and the vegetation and terrestrial animals in these systems will increasingly be affected by wave overwash during storms, reshaping and movement of islets and beaches, and salinization and rising of groundwater. For example, freshwater and brackish water wetlands will become more saline with increasing sea-water inundation and intrusion into shallow water tables. Species that are dependent on fixed islands for breeding, such as seabirds and sea turtles, are particularly susceptible to such change (Frederiksen et al., 2004). These episodic but progressive changes will reduce or eliminate endemic terrestrial species on many small islands over time. In addition, coral reef ecosystems in the region are likely to be affected by mid-century as the upward growth rates of corals are expected to slow in response to rising sea levels (Burke et al., 2011).

Over the long term (100-plus years), low islands face an existential threat due to rising sea levels. Dickinson (2009) describes how a mid-Holocene (~4,000–6,000 years ago) hydro-isostatic highstand in the tropical Pacific sea level drowned atoll rims and built reef flats at elevations of 1.0 to 2.4 m (~3 to 8 feet) above modern low-tide level (Figure 3-11). As late Holocene sea level declined, ambient high tide eventually fell below the surfaces of paleoreef flats. After that crossover date, stable atoll islets formed with underpinnings of resistant mid-Holocene paleoreef flats that protected the flanks of the islets from wave attack. With rising global sea level, ambient high-tide level will once again rise above the mid-Holocene low-tide level and another crossover will occur. This time it will submerge the resistant paleoreef flats and subject their unconsolidated sediment cover to incessant wave attack even before ambient sea level actually overtops the islets. Dickinson suggests future crossover dates ranging from the latter half of this century (2050–2080), with a rapid rate of SLR, to the first half of the next century (2100–2160), if SLR is slow. Beyond human habitability, over the long term, impacts will go beyond the loss of tangible artifacts and structures (Vitousek et al., 2004) to the intangible loss of a land base and the cultural traditions that are associated with it (Henry & Jeffery, 2008).

High islands

Many of the considerations noted above for low islands apply to the nearshore and coastal portions of high islands. Impacts to the built environment on low-lying portions of high islands will be much the same as those experienced on low islands. Unlike low islands, however, high islands have large uplands where facilities and infrastructure could be moved inland to reduce risk. With a tendency to be more developed, increased economic impacts in sectors such as tourism due to increased flooding and erosion are worth note. In Hawaiʻi, for example, where tourism comprises 26% of the state's economy, damage to tourism infrastructure, including the loss of Waikīkī Beach, could lead to an annual loss of $2 billion in visitor expenditures (Waikīkī Improvement Association, 2008).

On high islands, the beaches, dunes, coastal wetlands, and their associated species will face similar pressures to those on low islands. For example, sea-level rise is a particular threat to mangroves, as human infrastructure and/or steep volcanic topography are likely to restrict landward migration. In American Sāmoa, mangrove resilience to SLR shows a 0.2% annual loss, indicating that the Pacific Island mangrove may be substantially reduced by 2100 (Gilman et al., 2008). Other species and habitats may be able to move landward and upward as topography and human infrastructure allow.

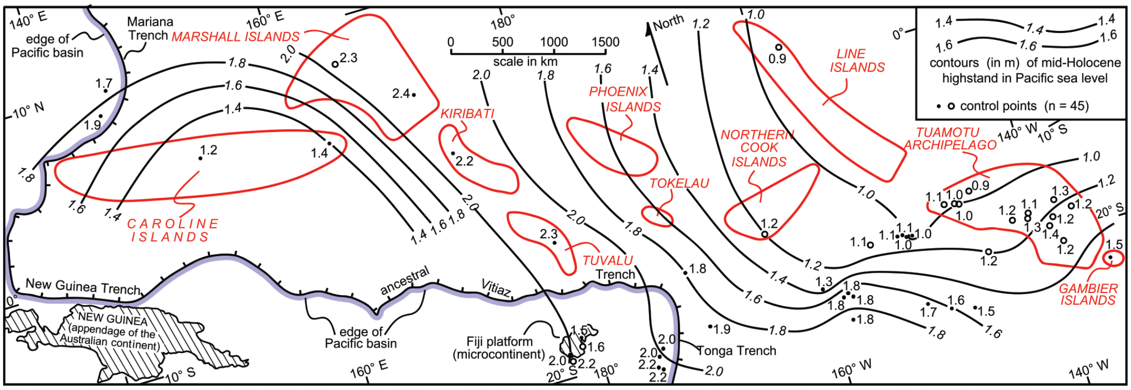


Figure 3-11 Contours of the magnitude (above modern sea level) of the hydro-isostatic mid-Holocene highstand in regional sea level across the tropical Pacific Ocean; solid dots are control points (number [n] = 27) from personal observations (Dickinson, 1998, 1999, 2000, 2001, 2003; Dickinson et al., 1999; Dickinson & Burley, 2007), and open dots are congruent control points (n = 18) from others (Pirazzoli & Montaggioni, 1986, 1988; Nunn, 1988, 2000; Woodroffe et al., 1990; Woodroffe & McLean, 1998; Grossman et al., 1998). For contouring, control points within the microcontinental Fiji platform were ignored from the perspective that isostatic upflexure of the platform under the enhanced load of deepening water offshore promoted emergence that partly counteracted SLR (Nakada, 1986). (From Dickinson, 2009.)

A number of government and university-based efforts are under way to help provide decision makers with actionable information needed to address the challenges associated with SLR and the increasing occurrence of coastal inundation. The University of Hawai'i, for example, is working with NOAA to create maps based on SLR scenarios to help identify vulnerable assets, assess impacts, and determine appropriate adaptive responses to sea-level rise. NOAA (through the NESDIS NCDC, NWS PEAC Center, NOS COOPS, and Coastal Storms Program) is working with other federal agencies, as well as university and international partners, to help advance our knowledge of extreme water levels and incorporate this information into products such as seasonal to annual "outlooks" and decadal to multidecadal "scenarios" that are targeted to meet local needs. More broadly and on a regional scale, entities such as PaCIS, Pacific RISA, PICCC, and others are working to grow a "network of networks" as a means to nurture essential partnerships, align complementary interests and activities, and thereby foster a regional culture of communication, coordination, and collaboration in support of climate adaptation planning and disaster risk reduction.

Summary

The key findings regarding regional sea level and coastal inundation in response to climate change are as follows:

- Since the early 1990s, the rate of globally averaged sea-level rise has increased to ~3.4 mm (a little more than a tenth of an inch) per year. This is twice the estimated rate for the 20th century as a whole.

- Regional sea-level trends may differ significantly from the globally averaged rate over multi-year to multidecadal time scales. For 1993–2010, the standard deviation of regional trends based on satellite altimetry is as large as the global mean trend, with the highest rates of regional SLR having occurred in the western tropical Pacific.
- Regional sea-level fluctuations at inter-annual to multidecadal time scales (e.g. ENSO, PDO) will combine with global sea-level rise. These fluctuations are largely wind-driven and represent a redistribution of water associated with climate variability. This suggests that the current high rates of regional SLR in the western tropical Pacific are not expected to persist over time, falling once the trade winds begin to weaken.
- Models suggest that global warming will raise global sea level significantly over the course of this century. The range of predictions is largely due in part to unresolved physical understanding of various processes, notably ice-sheet dynamics.
- Modeling studies have yielded conflicting results as to how ENSO and other climate modes will vary in the future. As a result, there is low confidence in the prediction of future climate states and their subsequent influence on regional sea level.
- Regional sea-level trends associated with climate change (i.e., distinct from natural variability) are predicted in climate models but not with sufficient confidence for definitive projections.
- Vertical land motion has been assessed at some islands based on continuous GPS measurements. Land motion trends generally are weak compared to global rates (~ <10%).
- For the region, extreme sea-level events generally occur when high tides combine with some nontidal residual change in water level. In the major typhoon zones (i.e., Guam, CNMI), storm-driven surges can cause coastal flooding and erosion regardless of tidal state. At present, trends in extreme levels tend to follow trends in mean sea level.
- Wave-driven inundation events are a major concern for all islands in the region. In situ wave observations are needed to better assess wave-driven flooding statistics.
- Increasing mean water levels and the possibility of more frequent extreme water-level events, and their manifestation as flooding and erosion, will threaten coastal structures and property, groundwater reservoirs, harbor operations, airports, waste water systems, sandy beaches, coral reef ecosystems, and other social and economic resources. Low islands are especially vulnerable over the near to mid-term (next 25 to 50 years), with impacts varying with location and depending on how natural sea-level variability combines with modest increases of mean levels.
- A number of efforts are under way in the region to identify vulnerable assets, assess potential impacts, and determine appropriate adaptive responses to sea-level rise and coastal inundation.

FOCUS ON IMPACTS

Case Study 3-1

A combination of processes creates extreme water levels and contributes to flooding and erosion

Episodic extreme water level events pose a serious risk to Pacific Island regions. Higher-than-normal sea levels, for example, allow more wave energy to pass over reef systems. Combined with high waves, this increases the possibility of inundation of low-lying coastal areas and low islands (e.g., atolls) and contributes to coastal erosion. This, in turn, can lead to saltwater intrusion, which damages freshwater sources and agricultural crops; damage to roads, houses, and other infrastructure; and destruction of critical habitat such as nesting sites for seabirds and turtles. Understanding and identifying the processes that cause such extreme events is essential to understanding impacts and informing disaster risk reduction as well as climate adaptation planning in a world where sea level is rising in response to a changing climate.

In December 2008, the Solomon Islands, Republic of the Marshall Islands (RMI), Federated States of Micronesia (FSM), and other low-lying islands in the Western North Pacific sub-region (Figure 3-12) experienced damage from ocean flooding due to a convergence of climate and weather factors:

- **High waves.** Low-pressure weather systems far to the north (near Wake Island) generated swells that were large, but not particularly extreme, ranging between 3 and 10 feet. These waves caused damage because they coincided with higher-than-normal sea levels.
- **Seasonal high tides.** In early to mid-December 2008, the tides were building to their spring stage, an increased tide range during full and new moons. Though the first large storm hit a week prior to the spring peak (Figure 3-13a), tide levels were still relatively high due to the twice-annual strengthening of local spring tides during November–February (and again May–August).
- **The influence of La Niña.** In the central and western Pacific, the northeast trade winds generally increase during the second half of the year, bringing higher sea levels. This pattern is exacerbated during a La Niña period. In December 2008, weak La Niña–like conditions existed, producing higher-than-normal sea levels (Figure 3-13b).
- **Long-term sea-level rise.** Since the 1990s, sea levels have risen about 7.87 inches (20 cm) in the Western North Pacific sub-region (Fig. 3-13b; regional view in Figure 3-4). This sea-level rise, the largest of any region in the world, is the result of a long-term increase in Pacific trade winds (Merrifield & Maltrud, 2011), similar to the effect of La Niña conditions but over a longer time frame.

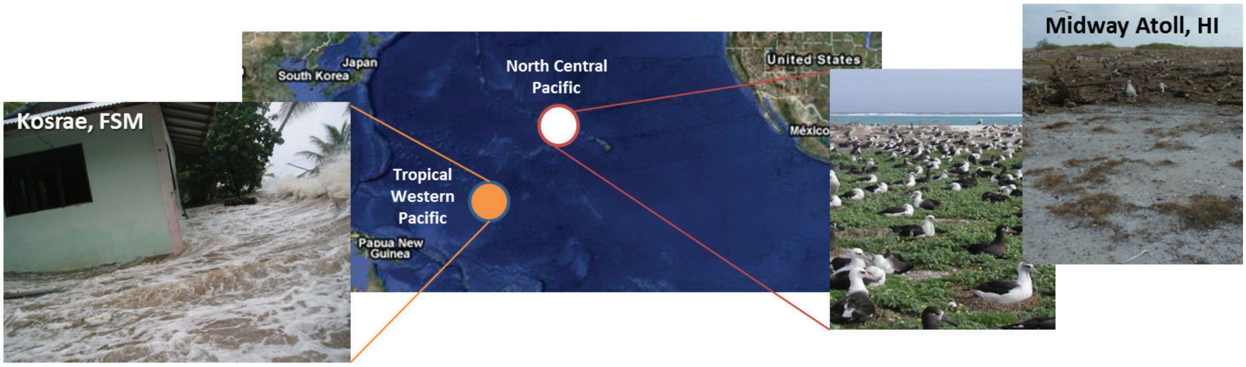


Figure 3-12 Locations of coastal inundation as measured by NOAA tide gauges: the Marshall Islands (orange) in December 2008, and Midway Atoll (white) in winter 2011. (Courtesy of US Fish and Wildlife Service, except for Kosrae image, which is courtesy of Kosrae Island Resource Management Agency staff.)

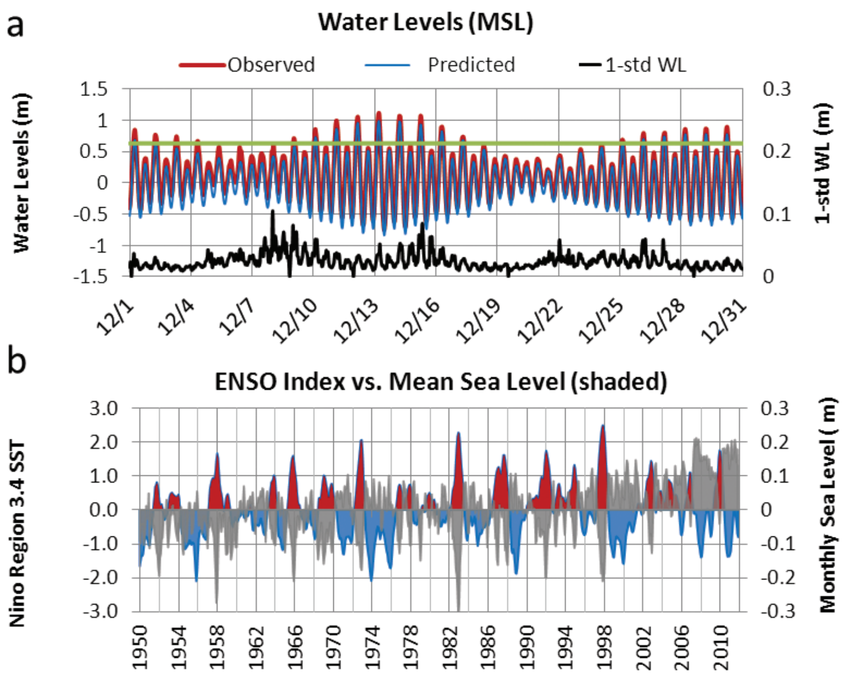


Figure 3-13 In mid-December 2008, the Marshall Islands experienced high seasonal spring (king) tides causing water levels to rise above the Mean Higher High Water (MHHW, green) level. Around this time (a) multi-day periods with enhanced wave activity and related swash motions at the shoreline occurred ~ Dec 8 and 15 seen as high variability within each hourly water-level measurement (1-std WL, Sweet et al., 2011). In (b), the ENSO Niño Region 3.4 anomaly (red/blue) shows elevated sea levels during cool phase/La Niña (blue) or warm phase/El Niño (red), which have steadily increased since about 1990. 0.1 m = 0.33 ft. (Data from NOAA Tide Station at Kwajalein, Marshall Islands.)

The result was widespread damage on numerous low-lying islands. Immediate impacts included eroded beaches, damaged roads, and flooding of houses. A state of emergency was declared on Majuro, capital of the Republic of the Marshall Islands, with damage topping $1.5 million (Wannier, 2011). In the Federated States of Micronesia, seawater contaminated aquifers, wells, wetlands, and farms, damaging or destroying nearly half of the nation's cropland (Fletcher & Richmond, 2010). Here, as well, a state of emergency was declared, sparked primarily by concerns about immediate and long-term food shortages. The coastlines on several islands were littered with debris, raising fears of a health crisis, particularly when local cemeteries were flooded.

In the winter months of 2011, a combination of high sea levels and large waves struck Midway Atoll on two different occasions. Midway and the other Northwestern Hawaiian Islands (NWHI; Figure 3-14) provide nesting sites for 95% to 99% (Arata et al., 2009) of the 1.3 million Laysan albatross (*Phoebastria immutabilis*) in the world and 95% of the world population of 132,000 black-footed albatross (*Phoebastria nigripes*). In January 2011, a powerful storm hit Midway Island, killing thousands of unhatched eggs and newly hatched chicks. The storm caused a drop in pressure that raised the sea level by more than 0.98 feet (0.3 m). At the same time, strong winds and waves battered the island. An even more severe storm hit Laysan Island in February, with large waves and winds of

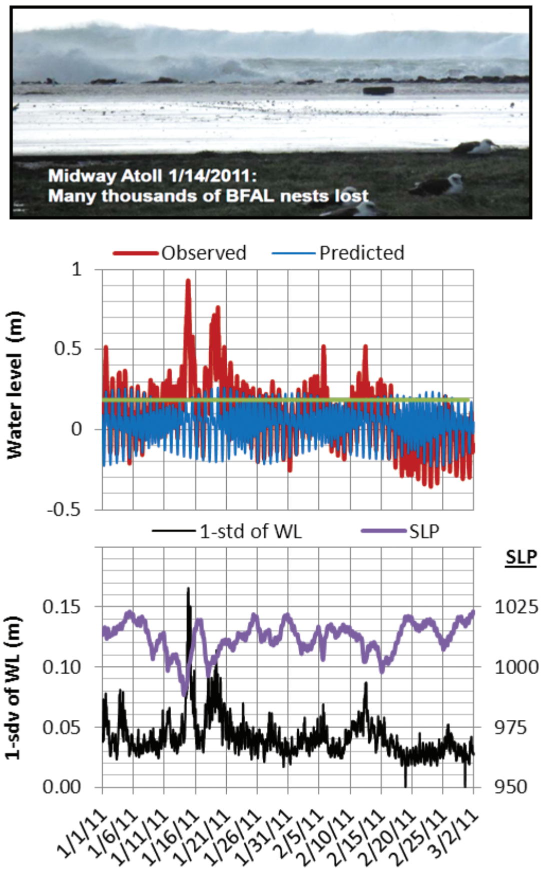


Figure 3-14 Photo (top panel) shows the impact of waves on the Midway Islands during a winter storm. Multiple extreme sea levels exceeded the level of Mean High High Water (MHHW, green line) by about 0.75 m in January 2011 and 0.3 m in February (red). Some storms overlapped with high spring tides (blue). As the storms passed overhead, sea-level pressure (SLP, purple) dropped and wave activity increased (black, 1-stdev of hourly WL as a proxy) causing a significant wave setup in water levels (red). BFAL = Black Footed Albatross. 1 m = 0.33 ft. (Courtesy of US Fish and Wildlife Service. Data from NOAA Tide Station at Midway Island.)

more than 74 miles per hour. This storm destroyed more than 40,000 Laysan albatross nests and 9,000 black-footed albatross nests (Flint et al., 2011). These birds tend to return to the same nest sites every breeding season, even after their nests are destroyed. However, as sea level rises, flooding events will become more frequent in albatross nesting zones, and breeding populations within the NWHI will drastically decline.

So-called mesoscale eddies are another phenomenon that has been observed to contribute to increased flooding and erosion (Firing & Merrifield, 2004). Unique to the Hawaiian Islands for the most part, these features are capable of producing a prolonged impact when they occur along with high tides and moderate-sized waves. In September 2003, a westward propagating circulating eddy was associated with the highest daily (average of hourly measurements) water level and highest monthly value ever recorded in Honolulu (Figure 3-15a, shown since 1932). Due to its large size, slow passage, and circulation characteristics (clockwise from a high sea surface in its center), the eddy raised sea levels by about 6 inches (15 cm) for nearly two months starting in late July 2003 (Figure 3-15b) (Firing & Merrifield, 2004).

During this period, there were numerous daily extremes (Figure 3-16, left), defined as daily maximum heights (based on hourly values) exceeding the 99th percentile relative to the long-term trend over 1980–2010 (black line in Figure 3-15a). Sea level peaked the last week of September (highest daily mean on September 28), when the seasonal cycle of sea level is also highest (typically more than 8 cm [3.15 inches] higher than its low in April/May) due to normal seasonal surface heating and related thermal expansion of the upper ocean. Also contributing to this absolute maxima, but in a more subtle manner, was the slow rise in relative sea level over the past century (about 0.059 inches/year or 1.5 mm/yr).

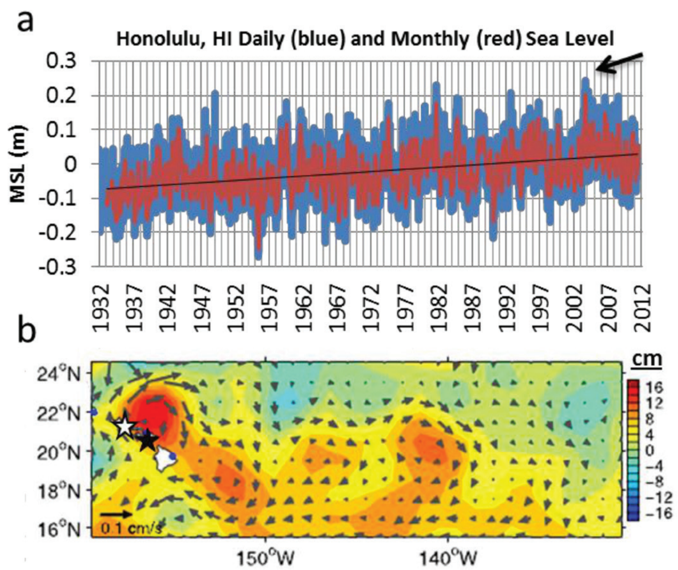


Figure 3-15 (a) Daily and monthly mean sea levels at NOAA Tide Gauge Honolulu (white star in (b)) are shown relative to the 1983–2001 mean sea level (MSL). The black line indicates the long-term relative sea-level rise (about 1.5 mm [0.059 in]/year); the arrow indicates the September 2003 event. (b) The gridded altimeter sea-surface height (SSH, contours in centimeters (cm), and mean circulation (vectors) for August 7, 2003, reveals the eddy directly north of the Hawaiian Islands. 0.1 m = 10 cm = 3.94 in. (Data in Figure 3-15a from NOAA; Figure 3-15b © 2004 American Geophysical Union. Reproduced/modified from Firing & Merrifield [2004] by permission of American Geophysical Union.)

This eddy was not necessarily a rare or unique event; in fact, there have been numerous eddies, which can be tracked by satellite altimeter (Figure 3-16, right). Eddies have been observed to originate far to the east of the Hawaiian Islands as well as in the lee (west) of the islands themselves. They are thought to form in response to changes in regional wind forcing related to El Niño-Southern Oscillation (ENSO) and from instabilities within the prevailing westward-flowing North Equatorial Current (Mitchum, 1995; Firing & Merrifield, 2004; Chen & Qiu, 2010). Although eddies occur on an inter-annual basis, they generally produce extreme events only when they combine with seasonal high tides and waves. Although storms have always caused flooding on low-lying islands of the Pacific, the concern today is that sea-level rise related to longer-term climate conditions will combine with storms to cause even more frequent and more damaging floods in the years ahead.

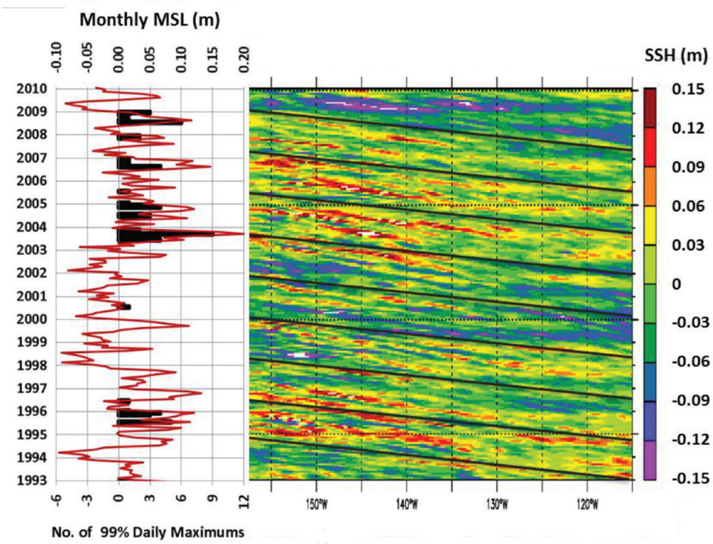


Figure 3-16 A time-longitude plot of SSH anomalies (right) along the altimeter track at 21.3°N shows that when high monthly mean sea levels at Honolulu (left, right line) are recorded, they often appear to originate further east along the same latitude range (right, eddies as red contours moving westward over the x-axis as time progresses on the left y-axis). 0.1 m = 0.33 ft. (©2004 American Geophysical Union. Reproduced/modified from Firing & Merrifield [2004] by permission of American Geophysical Union.)

FOCUS ON ADAPTATION

Case Study 3-2

Mapping sea-level rise in Honolulu

Rising sea levels along Hawai'i's coastlines will exacerbate many other episodic coastal hazards such as storm surge, tsunami, and hurricane inundation. The threat of rising ocean levels calls for strong leadership and proactive measures from federal, state, and local governments. Mapping the potential impact of sea-level rise (SLR) provides a basis for developing adaptation guidelines and choosing among a range of coastal land-use policy tools (Culver et al., 2010; Codiga & Wager, 2011). Maps allow communities to assess what needs protection and what form protection should take. Based on stakeholder workshops, agency surveys, and analysis by researchers at the University of Hawai'i, Codiga and Wager conclude that Hawai'i is likely to experience a sea-level rise of around 1 foot by 2050 and around 3 feet by the end of this century (Figure 3-17). Local and regional decision makers, land-use planners, and managers should consider this forecast as a guideline for development planning (e.g., SLR Policy Toolkit, *http://seagrant.soest.hawaii.edu/publications*).

Using these estimates combined with digital elevation models, the University of Hawai'i Coastal Geology Group has developed maps to help visualize the impact of elevated sea level on the island of O'ahu (see figures below). This work suggests that segments of shoreline and numerous low-lying inland areas will fall below the high-tide line later in the century as sea levels rise.

Low-lying areas that are not submerged will be increasingly vulnerable to inundation by high waves, storms, tsunami, coastal flooding, and extreme tides. Along the shoreline, the impacts are already being observed, including beach erosion and waves reaching over seawalls and other structures with increased frequency and magnitude. In areas of Honolulu and Waikīkī within five to eight blocks of the ocean, there is the potential for basements to flood, ground floors to be splashed by storm wave runup, sea water to come out of the storm drains, and flooding following heavy rains.

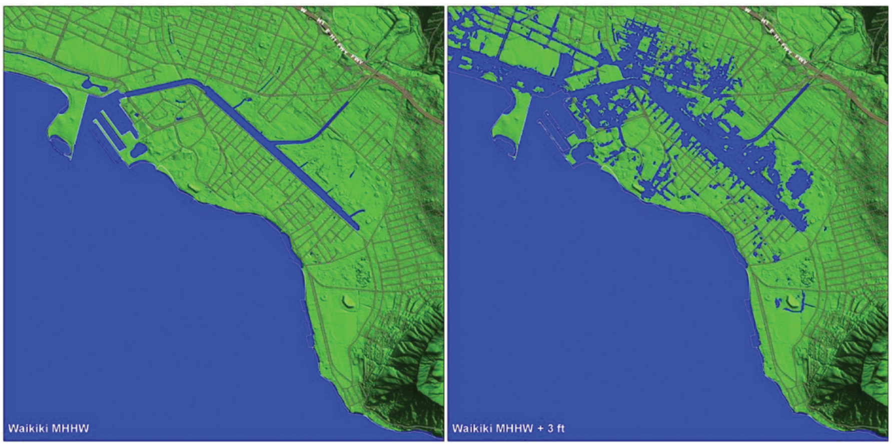


Figure 3-17 Waikīkī District: Areas shaded in blue on the left lie at or below 0.3 m above the current high-tide line; areas shaded in blue on the right lie at or below 0.9 m above the current high-tide line. The thin white line is the current shoreline. (Courtesy of University of Hawai'i Coastal Geology Group.)

Chapter 4

Marine, Freshwater, and Terrestrial Ecosystems on Pacific Islands

COORDINATING LEAD AUTHORS*

Stephen E. Miller (USFWS) and Britt Parker (NOAA CRCP)

CASE STUDY CONTRIBUTORS*

Stephen E. Miller (USFWS), Britt Parker (NOAA CRCP), Deanna Spooner (PICCC)

CONTRIBUTORS*

Fred Amidon (USFWS), Russell Brainard (NOAA PIFSC), Jeff Burgett (PICCC), Susan Cordell (USFS), David Duffy (University of Hawaiʻi at Mānoa), Stanton Enomoto (PICCC), Douglas Fenner (American Sāmoa DMWR), Melissa Finucane (East-West Center, Pacific RISA), Lucas Fortini (PICCC), Tom Giambelluca (University of Hawaiʻi at Manoa), Christin Giardina (USFS), Kevin Hamilton (IPRC, University of Hawaiʻi at Mānoa), Don Hess (College of the Marshall Islands), Jim Jacobi (USGS), Victoria Keener (East-West Center, Pacific RISA), Jean Kenyon (USFWS), Eric Kingma (WPFMC), Thomas Goreau (Global Coral Reef Alliance), Ove Hoegh-Guldberg (University of Queensland Global Change Institute), Greg Koob (NRCS), Len McKenzie (Queensland Department of Primary Industries and Fisheries), Rich McKenzie (USFS), Patricia Manley (USFS), John J. Marra (NOAA NCDC), Stephen E. Miller (USFWS), Britt Parker (NOAA CRCP), Dan Polhemus (USFWS), Jeff Polovina (NOAA NMFS), Bob Richmond (University of Hawaiʻi at Mānoa), Haldre Rogers (University of Washington), Jonathan L. Scheuer (Consultant), Heidi Schuttenberg, Karsten Shein (NOAA NCDC), Nori Shoji (NOAA NMFS), Rebecca Skeele (CNMI CRMO), Margaret H. Smith (East-West Center, Pacific RISA), Deanna Spooner (PICCC), Curt Storlazzi (USGS PCMSC), William V. Sweet (NOAA COOPS), Jared Underwood (USFWS), Adam Vorsino (USFWS)

*LISTED IN ALPHABETICAL ORDER

The islands and waters of the Pacific Islands provide the materials and means that allow the region's humans, plants, and animals to thrive. These fragile ecosystems not only support the fisheries and agriculture that the people of the region depend on for food and income, they also provide shoreline protection, places for recreation, shared cultural heritage, and many other benefits, all of which are at risk from climate change and local stress caused by human activities.

Climate variability and change threaten marine, freshwater, and terrestrial ecosystems through rising air and sea-surface temperature, sea-level rise (SLR), seasonal changes in precipitation, changes in the frequency and intensity of extreme weather events (hurricanes and typhoons, heavy rain events, and droughts), changes in solar radiation, and increasing ocean acidification (Figure 4-1). These physical and chemical changes affect many of the physical and biological processes on both land and in water and have cascading effects on water quality, species composition and diversity, wind, currents, waves, soil conditions, and habitat availability. All of these impacts will combine, often synergistically, to alter or in some cases eliminate important ecosystem function and reduce global biodiversity. Given the complex interconnectedness of these ecosystems and many of the species in them, we can only begin to understand the cascading impacts of these changes and the resultant impacts to the subsistence, culture, and way of life of the people of the Pacific Islands.

This vast region contains some of the most diverse ecosystems in the US, and in the case of the Pacific Remote Islands Marine National Monument and Papahānaumokuākea Marine National Monument, often the most pristine. Consequently, these areas offer a unique opportunity to better understand the impacts of climate change on coral reefs and on freshwater and terrestrial ecosystems of both low islands and high islands. In particular, the remote marine communities of the region allow a rare glimpse into ecosystems and ecological processes largely unaffected by human activities (Wilkinson, 2008; Pandolfi et al., 2005). In contrast, the freshwater and terrestrial environments within the region are more likely to have been significantly impacted by invasive species, and assessment of climate impacts on these ecosystems will need to consider not only changes in native ecosystems and species but also the interaction with invasive species that will also be responding to climate change.

Regional ecosystems overview

Marine ecosystems

Several key marine ecosystems in this region will be impacted by climate change, including those of the open ocean (pelagic, abyssal, deep coral) and those of insular or

---

This Chapter should be cited as:
Parker, B., & Miller, S. E. (2012). Marine, Freshwater, and Terrestrial Ecosystems on Pacific Islands. In V. W. Keener, J. J. Marra, M. L. Finucane, D. Spooner, & M. H. Smith (Eds.), *Climate Change and Pacific Islands: Indicators and Impacts*. Report for the 2012 Pacific Islands Regional Climate Assessment (PIRCA). Washington, DC: Island Press.

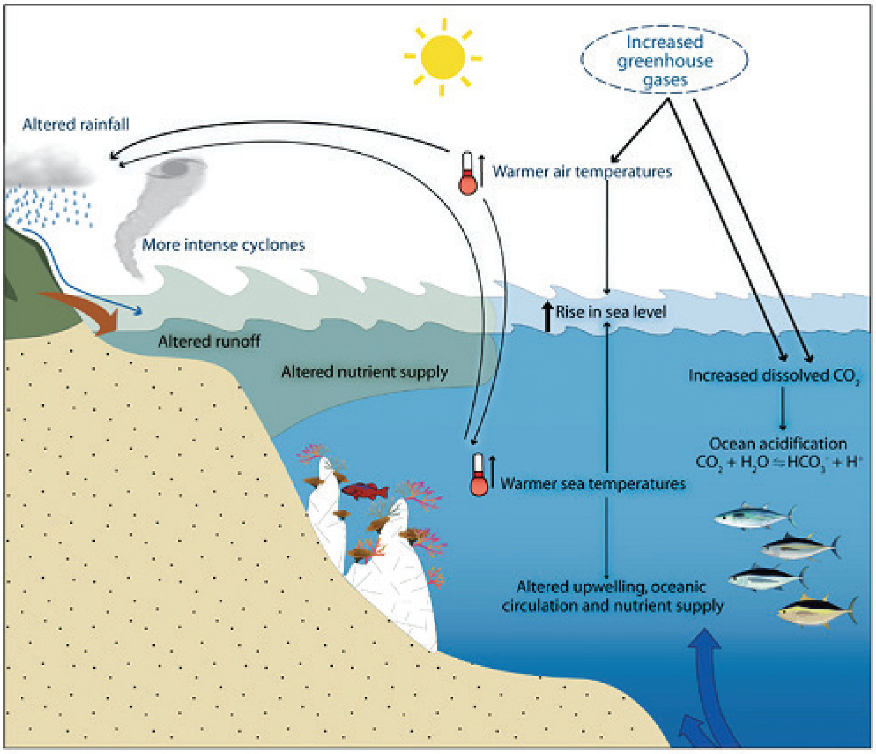


Figure 4-1 Generalized effects of increased greenhouse gases on oceanic and coastal ecosystems in the tropical Pacific. (From Bell et al., 2011.)

nearshore environments, such as shallow coral reefs, mesophotic reefs (those at water depths where light penetration is low), seagrass beds, intertidal flats, and mangroves. The communities within these ecosystems include many important species and groups of species: pelagic fish (such as tuna), reef fish, endangered sea turtles and monk seals, large marine mammals, corals, crustaceans, and phytoplankton, which form the base of the food web.

Terrestrial ecosystems

As discussed in the "Region profile" section of Chapter 1, terrestrial ecosystems in the Pacific Islands are divided between low islands and high islands. While atoll (low island) ecosystems are similar to strand and coastal plain ecosystems of high islands, they lack the elevation gradient and land area needed by species to adjust their distributions in response to climate change effects, such as SLR and changes in temperature and precipitation. Additionally, low island species have very little capacity to shelter from extreme weather events. High island species have, to varying degrees, the potential to track important habitat features as they change location with a changing climate.

Rainfall and temperature gradients on high islands (with high physical relief) offer a wide range of microclimatic conditions that support a diverse assemblage of plants and animals in coastal wetlands, high-elevation bogs, grasslands, wet, mesic and dry forests, subalpine and alpine landscapes, and intermittent and perennial streams. This is especially true in the main Hawaiian Islands, which support 86 distinct native plant communities and 20 alien-dominated plant communities from sea level up to 13,400 feet (Wagner et al., 1990). The responses of these diverse ecosystems to climate change are largely unexplored, with only a few studies from Hawaiʻi. The rate of climate-driven changes to native habitats in the Pacific Islands is unknown. Changes may happen slowly, driven by press-type disturbances such as ambient temperature rise or decreasing precipitation, or rapidly, driven by pulse-type disturbances such as extreme storms. This remains one of the major topics of interest for understanding how terrestrial ecosystems will respond to climate change, and it will be made more challenging by the added effects of invasive species.

Freshwater ecosystems

Freshwater ecosystems in the Pacific Islands are a critical human resource and add significantly to native island biodiversity. Coastal wetlands, while highly disturbed by invasive species and human usage, still provide important habitat for Pacific Island waterbirds, and high-elevation wetlands support unique natural plant communities. Stream systems are found only on high islands and are home to freshwater snails and arthropods, as well as a suite of fish, snails, and shrimp that are amphidromous (whose larval stages occur in the ocean). These latter species provide a direct link between freshwater and marine environments. Consequently, the future success of these species will depend on how ocean acidification and other marine effects of climate change may impact larval development and growth, as well as recruitment of these larval stages back into freshwater streams.

Historic and projected trends

The general climate state in the Pacific Islands has been described and summarized in Chapter 1 of this report, and the "Indicators of a changing climate in the Pacific Islands region" section of that chapter summarizes the general trends in the key climate variables across the region. This section focuses on features of climate that may be particularly important to marine, freshwater, and terrestrial ecosystems in the geographic sub-regions: the Central North Pacific (CNP; Hawaiʻi and the Northwestern Hawaiian Islands [NWHI]), the Western North Pacific (WNP; Commonwealth of the Northern Mariana Islands [CNMI], Republic of Palau [RP], Federated States of Micronesia [FSM], and the Republic of the Marshall Islands [RMI]), and the Central South Pacific (CSP; American Sāmoa). The following section broadly describes ecosystem impacts caused by the interplay of these climate features.

Surface air temperature

Historical and current observations of surface air temperature (SAT) across the tropical and subtropical Pacific Islands provide a high level of confidence for significant warming trends in the CNP, WNP, and CSP. In the CNP, terrestrial areas of Hawaiʻi have warmed rapidly, especially since the 1970s, with more warming at higher elevations and at night. See the "Historic and current trends" section in Chapter 2 for a more in depth discussion on SAT.

Sea-surface temperature

Historical and current observations of sea-surface temperature (SST) across the region provide high confidence that SST is rising. Water temperatures remained relatively constant or saw weak warming from the 1950s to the 1970s in the WNP and a cooling over the same period in the CSP. Since the 1970s, more rapid warming has occurred at a rate of 0.07° to 0.23°C (+0.13° to 0.41°F) per decade depending on the location. Projected increases in SST for the region range from 0.6° to 0.7°C (1.1° to 1.3°F) by 2030, 0.9° to 1.4°C (1.6° to 2.5°F) by 2055, and 1.3° to 2.7°C (2.3° to 4.9°F) by 2090 under B1 and A2 emission scenarios (Australian Bureau of Meteorology & CSIRO, 2011).

Precipitation and extreme rainfall events

Historical trends in the WNP sub-region showing changes in annual and seasonal rainfall trends for FSM and RP from the 1950s to 1990s are not statistically significant, while negative annual and dry-season trends for RMI are statistically significant. Rainfall projections for the WNP sub-region indicate that wet-season, dry-season, and annual averages of rainfall will increase (Australian Bureau of Meteorology & CSIRO, 2011). There are no clear historical trends for the CSP sub-region. Precipitation in the sub-region is projected to either change very little during the dry season or possibly decrease. An increase in rainfall is projected for the wet season (Australian Bureau of Meteorology & CSIRO, 2011). Precipitation trends in the CNP (Hawai‘i) show moderate cyclical dependence on both the El Niño-Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) (Chu & Chen 2005); however, Chu et al. (2010) show that droughts are increasing as the precipitation regime over the islands has become more dominated by light rainfall and fewer heavier rain events. See the "Historic and current trends" section in Chapter 2 for a more in-depth discussion on precipitation and extreme rainfall events.

Sea-level rise

Rates of sea-level rise (SLR) derived from satellite altimetry since 1993 range from 2 to 5 mm/year (~0.08 to 0.20 inches/year) within the CNP and CSP, and ≤10 mm/year (0.39 inches/year) throughout much of the WNP (see Figure 3-4 in Chapter 3). As compared to the global mean rate of 3.2 ±0.4 mm/year (0.13±0.02 inches/year) (Nerem et al., 2010), these trends are relatively high and of significant concern if they persist in the future due to the low-lying island topography. The ramped-up rates in the WNP are attributed to strengthened trade wind forcing (Merrifield, 2011; Merrifield & Maltrud, 2011). However, it is not clear whether or not the current rates in SLR and related sea-surface height pattern will remain (associated with a shift in the underlying state of the ocean-atmosphere system) or if they will eventually settle down (a function of climatic-scale variability). See the "Historic and current trends" section in Chapter 3 for a more in-depth discussion on SLR.

Ocean acidification

When CO_2 is absorbed by seawater, chemical reactions occur that reduce seawater pH, carbonate ion (CO_3^{2-}) concentration, and saturation states of the biologically important

$CaCO_3$ minerals calcite (Ω_{ca}) and aragonite (Ω_{ar}) in a process commonly referred to as ocean acidification (Feely et al., 2009). Historical and current observations of aragonite saturation state (Ω_{ar}) show a decrease from approximately 3.8 to 3.6 in the last 20 years in the CNP. In the WNP, it has declined from approximately 4.5 in the late 18th century, to 3.9 in 2000, and to 4.1 in the CSP (Australian Bureau of Meteorology & CSIRO, 2011).

Projections from CMIP3 models indicate the annual maximum aragonite saturation state will reach values below 3.5 by 2035 in the waters of the RMI, by 2030 in the FSM, by 2040 in RP, and by 2060 around the Samoan archipelago. These values are projected to continue declining thereafter (Australian Bureau of Meteorology & CSIRO, 2011).

Tropical cyclones

While there is little consensus at this point as to how storms in the Pacific Ocean may be affected by global climate change (IPCC, 2007; Collins et al., 2010; Knutson et al., 2010), most agree that increases in atmospheric and oceanic temperatures will result in changes to storm frequency, storm tracks, and the intensity of storms. These changes will, in turn, modify the timing, magnitude, and patterns of large storm waves in the ocean basin. Current information indicates that tropical cyclone activity for the CSP is projected to lessen, while activity in the WNP will increase significantly (Emanuel, 2005). The projections of potential intensity of tropical cyclones in these areas all show low, but significant, increases over the next 70 years (Yu et al., 2010). Projections for the eastern Pacific, which could affect Hawai'i, give variable results with no clear trend (Emanuel, 2005). The projected intensity of tropical cyclones in these areas shows low but significant increases over the next 70 years (Yu et al., 2010). The paths of cyclones may also shift more toward the CNP as a result of global warming (Li et al., 2010).

Impacts to marine ecosystems

In marine ecosystems, the changes in SST, SLR, ocean acidification, and precipitation lead to other physical, chemical, and biological changes in the open and nearshore waters, some of which are better understood than others. Changes in SST in conjunction with potential changes in wind, wave, and current patterns can lead to a change in stratification. This in turn can lead to changes in nutrient availability to the photic zone and therefore changes in phytoplankton abundance, size, and diversity. Because these organisms form the base of the oceanic food web, this in turn can lead to changes in patterns of abundance and distribution of key fisheries species, as can simple changes in SST alone (Le Borgne et al., 2011; Polovina et al., 2011). Population connectivity in coral reefs and other ecosystems may also shift as winds, waves, current patterns, and temperature regimes are altered. This could impact the ability of reefs to recover from bleaching events and to be reseeded by larvae from other reef areas. Larval fish distribution could also be impacted (Munday et al., 2009). Waves, both acute (storm-generated) and chronic (wind-driven waves with addition of SLR), can change the geomorphology of islands and the coral reefs that surround them. This in turn can result in the loss and/or creation of habitat, which will also affect species distribution. Changes in rainfall patterns and increasing frequency and intensity of extreme events can lead to greater runoff of sediment and land-based sources of pollution, especially in high islands. This can lead to changes in water quality due to a decrease in water clarity and an increase in algal blooms that can impact seagrass beds and coral reefs. Rising sea level can inundate low-lying landfills, which can also affect water quality when toxicants are released into the marine environment. Impacts to specific marine ecosystems are expanded on below.

Open ocean

A recently published vulnerability assessment of tropical Pacific fisheries and aquaculture offers a succinct summary of the relationship between important pelagic fisheries, physical ocean properties, and variables that will be impacted by climate change:

> *The production of the four species of tuna, and other large pelagic fish, is underpinned by food webs based not only on the photosynthetic productivity of phytoplankton (called primary production) in the sunlit surface layer (photic zone) of the ocean, but also by bacteria and detritus, derived from phytoplankton. The energy produced through primary production moves through a "trophic pyramid" [Figure 4-2] via a range of zooplankton (such as copepods and larval fish), macrozooplankton (including jellyfish and salps) and micronekton (such as squid, shrimp and small fish), to sustain tuna and other large pelagic fish. The availability of the nutrients that underpin the food web for tuna, together with suitable water temperatures and dissolved oxygen levels, determine the distribution and abundance of tuna and other large oceanic fish across the Western and Central Pacific Ocean. Therefore, the responses of phytoplankton, zooplankton and micronekton to changes in the ocean processes that deliver nutrients to the photic zone, and to changes in the physical and chemical properties of the ocean projected to occur as a result of global warming and ocean acidification are expected to affect all life history stages of large oceanic fish. (Le Borgne et al., 2011)*

Models project that between 2000 and 2100, the area of the subtropical biome (ecological community of plants and animals) will expand by 30%, while the area of temperate and equatorial upwelling biomes will decrease by 34% and 28%, respectively (Polovina et al., 2011). This is due primarily to enhanced stratification and a northward shift in the mid-latitude westerly winds under a changing climate. The important implication of this shift is that over the century, the total biome primary production and fish catch is projected to increase by 26% in the sub-tropical biome and decrease by 38% and 15% in the temperate and the equatorial biomes, respectively.

In addition to changes in productivity and fish catch, the boundaries of areas that are suitable for key fisheries species will shift, meaning changing availability and effort for some islanders to catch the fish. For example, two areas where the subtropical biome boundary exhibits the greatest movement is in the northeast Pacific, where it moves northward by as much as 1,000 km (621 miles) per 100 years, and at the equator in the central Pacific, where it moves eastward by 2,000 km (1,243 miles) per 100 years (Figure 4-3) (Polovina et al., 2011). Also, as SST rises, new thermal habitat will form, meaning different species distribution and composition, which will also affect fisheries. These types of impacts are already being observed as a function of ENSO on interannual scales, and this provides some insight into future impacts of climate change on food security for many of the Pacific Islands.

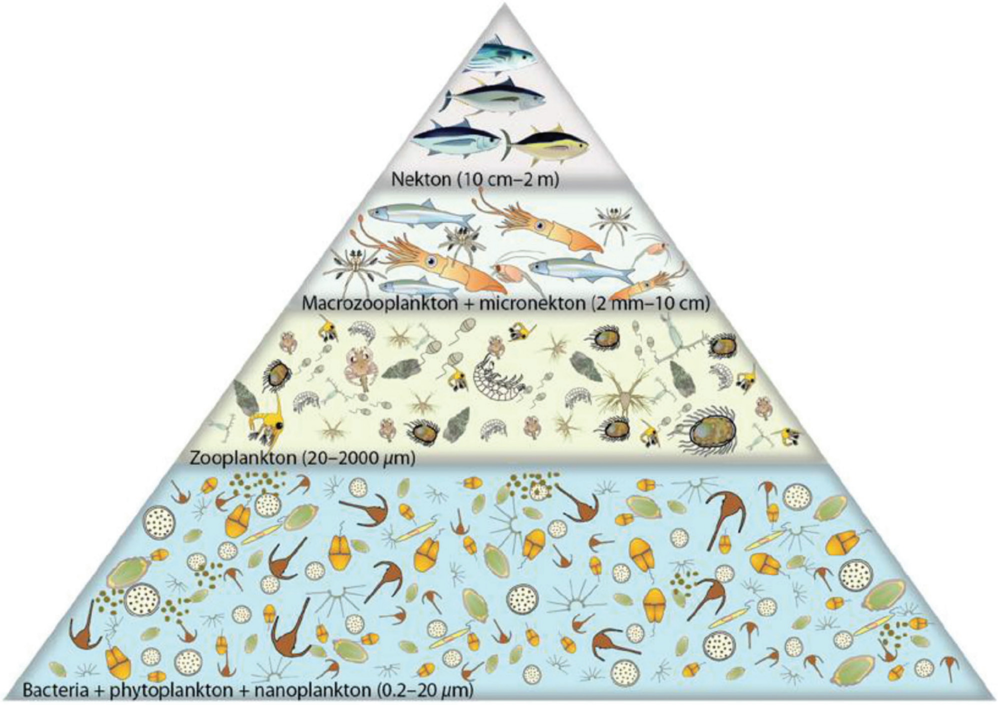


Figure 4-2 Generalized trophic pyramid for the tropical Pacific Ocean. The base of the food web consists of bacteria, small phytoplankton, and protists (nanozooplankton), 0.2 to 20 μm in size. These organisms are ingested by zooplankton, such as crustaceans, molluscs, or tuna larvae, up to a size of 2,000 μm. In turn, zooplankton are consumed by macrozooplankton, such as jellyfish, and micronekton, such as squid, shrimp, and small fish. Micronekton and, to a lesser extent, macrozooplankton are the prey for tuna and other large pelagic fish at the top of the pyramid. (From Le Borgne et al., 2011.)

There will also be impacts to the economically important tuna fishery in the Pacific Islands region. These impacts could be high, but the level of certainty about this is low. One ecosystem model coupled with a climate model indicates that under both A2 and B1 scenarios, by 2035 the total fishery catch for skipjack tuna increases by about 19% overall (11% for the western fishery and 37% for the eastern fishery), with no change for bigeye tuna. By 2,100 under the A2 scenario, however, the catch for both skipjack and bigeye will decline overall by 8% and 27%, respectively, with important spatial differences within the region. The western Pacific is projected to show the greatest declines in both fisheries (21% for skipjack and 34% for bigeye), whereas the eastern Pacific is projected to show an increase of 27% for skipjack and a decline of 18% for bigeye (Lehodey et al., 2011).

Coral reefs

Mass coral bleaching is caused by unusually high water temperatures, 1° to 2°C (1.8° to 3.6°F), above the normal summer maxima lasting for 3 to 4 weeks or more, and strong El Niño events are correlated with many of the major bleaching events in recent years

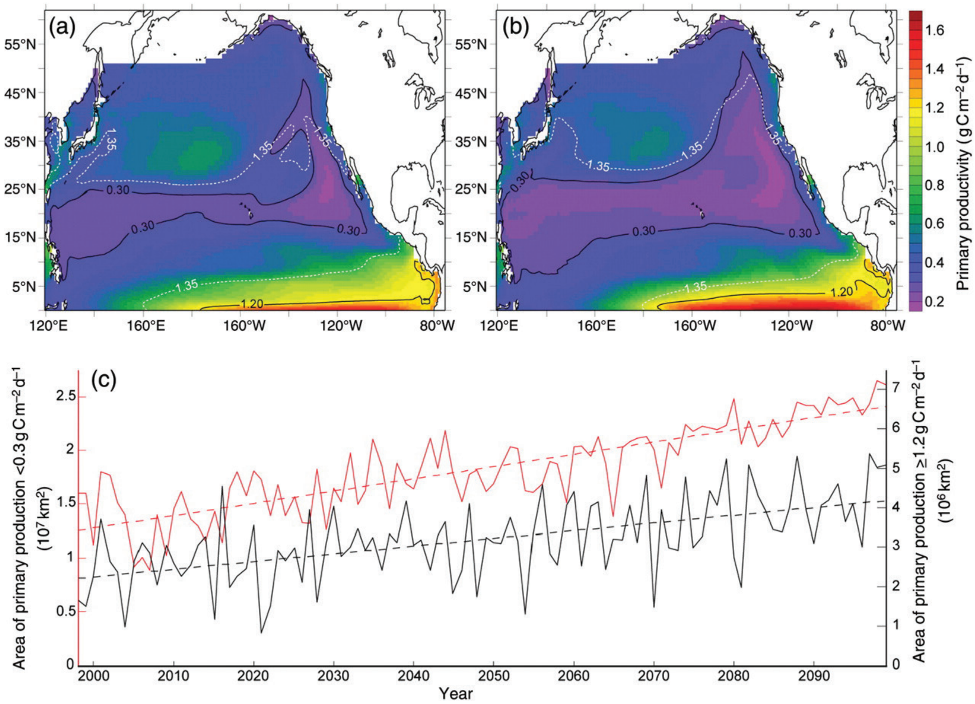


Figure 4-3 Mean depth-integrated primary production, (a) 1998–2017, (b) 2080–2099, (c) time series of the area with primary production, <0.3 g C m^{-2} d^{-1} in the subtropical biome (red line) and the time series of the area with production ≥1.2 g C m^{-2} d^{-1} in the Equatorial Upwelling biome. Dashed white lines in (a) and (b) indicate the biome boundaries. (From Polovina et al. [2011] by permission of Oxford University Press.)

(Hoegh-Guldberg, 1999; Strong et al., 1997). These conditions result in the breakdown of the symbiotic partnership between the zooxanthellate algae, which live in the tissue of coral, and the coral itself. The algae are expelled, which results in the loss of one of the main energy sources for the coral. While corals can recover from bleaching events of short duration, mortality can result from longer or more intense events. The increased frequency and intensity of bleaching events projected with increasing SST will leave corals little time for recovery (Sheppard, 2003), and the stress of bleaching events may impact their reproductive success, leave corals more susceptible to disease, and reduce their resilience to the next bleaching event. Recent predictions are that by 2050, many of the reefs in the Pacific will bleach annually (Figure 4-4) based on the A1B emissions scenario (Burke et al., 2011). Annual bleaching has already been reported from some warm pools in American Sāmoa (Fenner & Heron, 2008).

The process of ocean acidification reduces the availability of biologically important calcium carbonate minerals, which are the building blocks for the skeletons and shells of many marine organisms. Aragonite is particularly important to reef-building coral; an aragonite saturation state that is optimal for corals to form their skeleton is greater than 4.0, a state of 3.5 to 4.0 is adequate, 3.0 to 3.5 is marginal, and less than 3.0 is extremely marginal (Langdon & Atkinson, 2005). A recent report estimated aragonite saturation state for CO_2 stabilization levels of 380ppm, 450ppm, and 500ppm, which correspond

FREQUENCY OF FUTURE CORAL REEF BLEACHING EVENTS IN THE 2030s AND 2050s

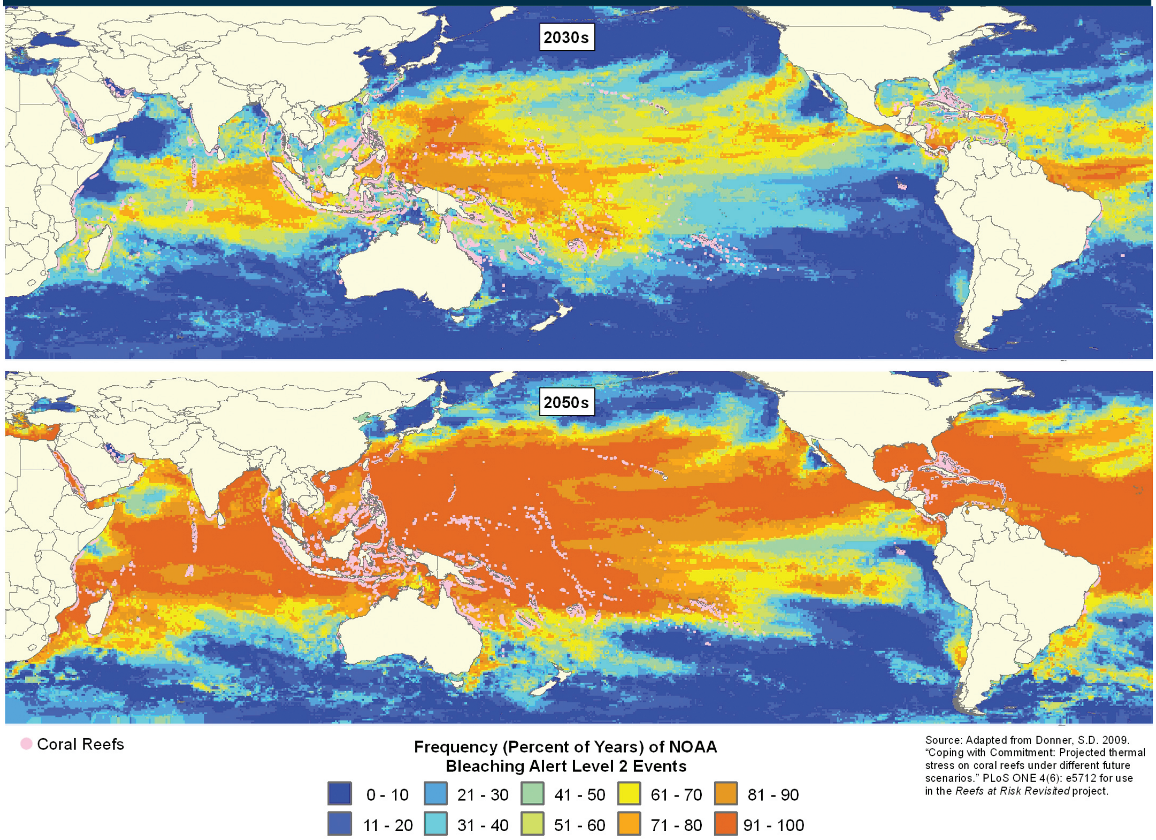


Figure 4.4 Frequency of future bleaching events in the 2030s and 2050s, as represented by the percentage of years in each decade where a NOAA Bleaching Alert Level 2 (i.e., severe thermal stress) is predicted to occur. Predictions are based on an IPCC A1B (business-as-usual) emissions scenario and adjusted to account for historical temperature variability but not adjusted by any other resistance or resilience factors. (From Burke et al., 2011. Data adapted from Donner [2009], "Coping with Commitment: Projected thermal stress on coral reefs under different future scenarios.")

approximately to the years 2005, 2030, and 2050 under the IPCC A1B (business-as-usual) emissions scenario (Figure 4-5) (Burke et al., 2011). By 2030, conditions around most coral reefs are only adequate or marginal for calcification to take place. Observed and experimental impacts of ocean acidification on coral reefs include lower calcification rates; more fragile reef structures; reductions in coral diversity, recruitment, and abundance of structurally complex reef framework builders; and shifts in competitive interactions among taxa, which can change the complexity of the reef structure (De'ath et al., 2009; Fabricius et al., 2011). Ocean acidification could have more far-reaching implications; recent work by Montenegro et al. (2011) suggests that the largest mass extinction event on record (Permian-Triassic Boundary extinction) corresponded to a period of an acidic ocean, and it puts forth this acidity as one of the potential kill mechanisms.

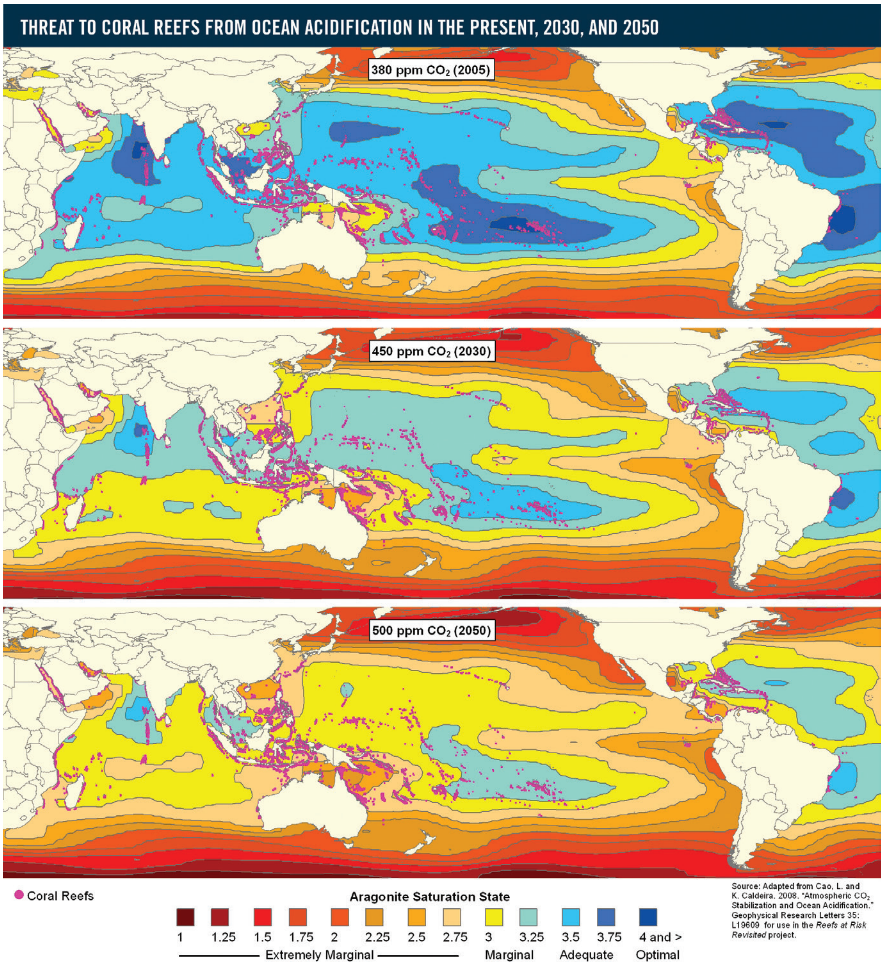


Figure 4-5 Estimated aragonite saturation state (an indicator of ocean acidification) for CO_2 stabilization levels of 380 ppm, 450 ppm, and 500 ppm, corresponding approximately to the years 2005, 2030, and 2050 under the IPCC A1B (business-as-usual) emissions scenario. (From Burke et al., 2011.)

While increasing SST and ocean acidification will have significant impacts to coral reefs, other climate change impacts could potentially contribute to reef degradation, including SLR, changes in storm frequency and intensity, and changes in ocean circulation and upwelling. Though coral growth and reef accretion rates in the Indo-Pacific are highly variable (Montagionni, 2005), current rates of SLR are thought to not directly threaten healthy coral reefs, and in the case of some reef flats, an increase in SLR has resulted in increased coral cover (Brown et al., 2011). However, SLR can lead to greater coastal erosion, especially during storm events, exposing reefs located adjacent to less stable shorelines to greater rates of sedimentation and re-suspension of seabed sediments, resulting in more turbidity (Field et al., 2011; Storlazzi et al., 2011). Furthermore, given other factors on growth (bleaching and ocean acidification), rapid SLR would represent an extreme challenge for coral reefs. Changes in storm frequency and intensity and storm tracks will also modify the timing, magnitude, and patterns of large storm waves in the ocean basin. There have been a number of efforts illustrating that coral reef morphology and coral species distribution in the Pacific Ocean are strongly controlled by wave energy (Storlazzi et al., 2003, 2005; Engels et al., 2004). Therefore, these changes may result in not only direct physical damage, increased runoff, and reduced water quality but also potential long-term impacts to species distribution and patterns of reef growth. Finally, ocean circulation patterns are important drivers of the productivity, functions, and connectivity of coral reefs and many of the organisms that inhabit them. Projected changes in the magnitude, location, and patterns of currents and associated upwelling zones could lead to changes in the genetic structure and connectivity of coral reefs and alter nutrient availability, which may alter the local ecosystems (Hoegh-Guldberg et al., 2011).

The threats that climate change presents to coral reefs are further compounded by the fact that coral reefs are also threatened by local stressors, such as fishing practices, land-based sources of pollution, sedimentation, disease, physical damage from anchors and vessels, coastal development, and invasive species. The impacts from these threats lower the resilience of reefs to climate change. In *Reefs at Risk Revisited* (Burke et al., 2011), maps showing reefs classified by present integrated threats from local stressors with projected thermal stress and ocean acidification for 2030 and 2050 indicate that many of the western Pacific reefs are highly or very highly threatened presently, and that increased threat will spread across the Pacific in coming decades (Figure 4-6). Based on the rate of coral loss reported over the past 20 years as well as the projected effects of more frequent coral bleaching and ocean acidification, average coral cover throughout the Pacific is expected to decline to 15% to 35% by 2035 compared with 20% to 40% in 2007 (Bruno & Selig, 2007; Hoegh-Guldberg et al., 2011). Coral death will cause changes in the complexity and structure of reef habitat. This in combination with other stressors will also affect coastal fisheries, including those coral dependent and reef associated, by contributing to a further loss of habitat (Figure 4-7).

Seagrass beds, mangroves, and intertidal flat complexes

The mosaic of seagrass beds, intertidal flats, and mangroves in the Pacific provides nursery areas and feeding grounds for fish species, habitat for crustaceans and invertebrates, shoreline protection and wave dampening, and improved water quality due to trapping of nutrients, sediments, and pollutants that run off from land (Waycott et al., 2011). These areas already face the threat of coastal development, and further losses are expected to occur as a result of climate change impacts, including heat stress due to rising air and water temperature, loss of suitable habitat due to sea-level rise, increased sedimentation due to greater runoff, and damage from potentially more severe cyclones and storms (Waycott et al., 2011).

Mangrove forests usually occur along low-energy shorelines between low-tide and high-tide levels, and species have evolved to exist along a continuum of salinities and inundation with sea water (Waycott et al., 2011). Mangroves will potentially be impacted by increasing air temperatures, SLR, changes in frequency and intensity of storms, and changes in rainfall patterns (Grantham et al., 2011). Mangroves have a high tolerance for

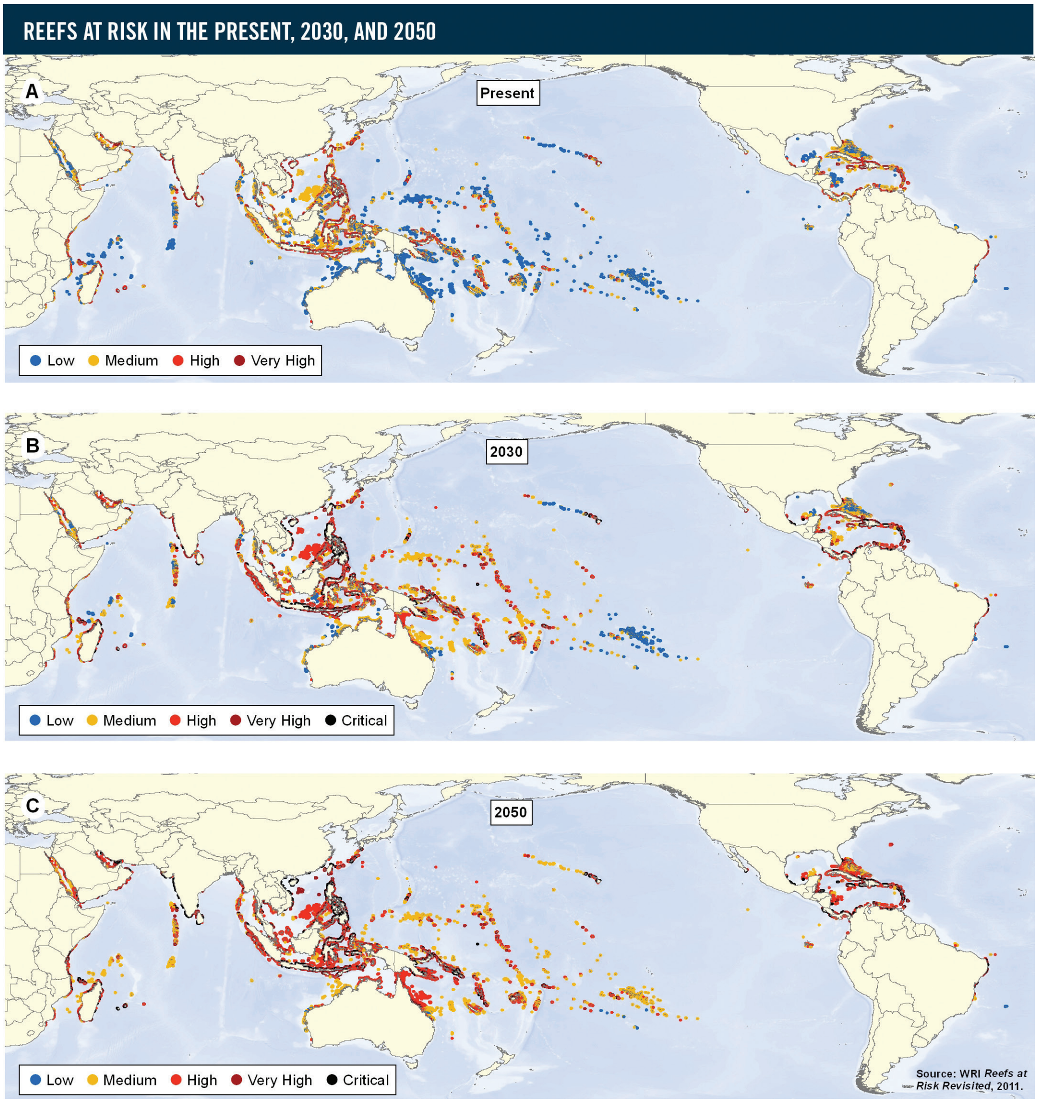


Figure 4-6 Map A (top) shows reefs classified by present integrated threats from local activities (i.e., coastal development, overfishing/destructive fishing, marine-based pollution, and/or watershed-based pollution). Maps B and C show reefs classified by integrated local threats combined with projections of thermal stress and ocean acidification for 2030 and 2050, respectively. Reefs are assigned their threat category from the integrated local threat index as a starting point. Threat is raised one level if reefs are at high threat from either thermal stress or ocean acidification, or if they are at medium threat for both. If reefs are at high threat for both thermal stress and acidification, the threat classification is increased by two levels. The analysis assumed no increase in future local pressure on reefs, and no reduction in local threats due to improvements in management. (From Burke et al., 2011.)

Types of species	Emissions scenarios		
	B1/A2 2035	B1 2100	A2 2100
Coral-dependent	-50%	-90%	-100%
Reef-associated	0%	-20 to -40%	-20 to -80%
Generalist	0%	0%	-10 to -20%
All demersal fish	**-2 to -5%**	**-20%**	**-20 to -50%**

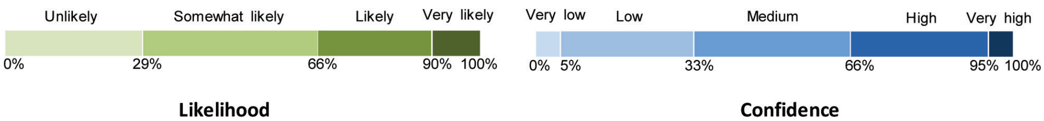


Figure 4-7 Projected changes in productivity of the demersal fish component of coastal fisheries under low (B1) and high (A2) emissions scenarios in 2035 and 2100. The estimated responses of broad types of demersal fish are also shown. The likelihood of these responses (especially for A2 in 2100) is low to medium. (From Pratchett et al., 2011.)

heat stress compared to many plants, though changes in SAT and SST may affect species distribution and composition and growth rate, and potentially change the timing of flowering and fruiting (Field, 1995; Ellison, 2000). SLR-induced erosion and inundation is a major threat to mangroves, especially if it is sudden or there is no path for landward migration (Ellison, 2000). Mangroves may also be able to move landward in response to SLR (Gilman et al., 2008). However, an extrapolation of current data indicates SLR in American Sāmoa will result in a 0.2% annual loss of mangrove area over the next century (Gilman et al., 2008). Changes in rainfall patterns can alter the magnitude and timing of freshwater flows to the nearshore environment, leading to changes in salinity and mangrove community composition (Field, 1995), and much like coral reefs and seagrass beds, mangroves can be destroyed by intense storms and cyclones.

Increasing SSTs are likely to result in changes in seagrass species distribution, sexual reproduction, growth rates, and changes in their carbon balance (Grantham et al., 2011). SLR will likely result in loss of ideal habitat along the deeper edge of meadows but result in more habitat at the landward bed edge. Changes in rainfall patterns, wave and current dynamics, and sea level can lead to changes in sedimentation and re-suspension of sediment, which reduce light availability to seagrass; these changes in water quality may be compounded by runoff of sediments, nutrients, and land-based sources of pollution (Short & Neckles, 1999; Björk et al., 2008). Additionally, while increasing levels of dissolved CO_2 could potentially have a positive effect by increasing photosynthesis, they also might stimulate epiphytic algal growth, which blocks light to the seagrass, especially in areas that are enriched in nutrients; thus, the potential benefits are likely to be outweighed by the negative impacts of climate change (Short & Neckles, 1999; Björk et al., 2008).

The role of intertidal flats—the transition zone between shoreline/sandy beach/mangrove forested areas and zones where seagrass and coral reefs can occur in the tropical

Pacific—is poorly understood. These habitats can play an important role in primary production and nutrient cycling through the benthic microalgae communities that live there; provide habitat for many organisms, including burrowing invertebrates that provide subsistence for human communities; and help mediate pollution though bacterial denitrification (Waycott et al., 2011). SLR is the largest concern for intertidal flats, especially in areas where the habitat cannot expand landward or where rates of sedimentation do not keep up with SLR. Increasing SAT and SST, changes in nutrient availability/terrestrial runoff, and changing ocean pH are all climate-related impacts that could alter species composition and distribution and levels of productivity, but more research is needed to fully understand the impacts of climate change to these habitats (Webster & Hill, 2007).

A recently published vulnerability assessment of tropical Pacific fisheries and aquaculture (Waycott et al., 2011) summarized the impacts to mangrove and seagrass ecosystems based on the B1 and A2 emissions scenarios at 2035 and 2100 with respect to different climate variables (Figure 4-8). Human activities that threaten these habitats, including unsustainable mangrove harvesting, habitat destruction, dredging, destruction of seagrass beds, and so forth, will exacerbate the impacts of climate change.

Scenario	Variable							Integrated vulnerability
	Light	Temp.	Rainfall	Nutrients	CO_2	Cyclones	Sea level	
Mangroves								
B1/A2 2035	Low (-)	Very low (-)	Low (+/-)	Low (+/-)	Very low (+/nil)	Moderate (-)	High (-)	Moderate
B1 2100	Low (-)	Very low (-)	Moderate (-)	Low (+/-)	Very low (+/nil)	Moderate (-)	Very high (-)	High
A2 2100	Low (-)	Very low (-)	Moderate (-)	Low (+/-)	Very low (+/nil)	Moderate (-)	Very high (-)	Very high
Seagrasses								
B1/A2 2035	Moderate (-)	Moderate (-)	Moderate (-)	Low (+/nil)	Very Low (+)	Moderate (-)	Low (-)	Moderate
B1 2100	Moderate (-)	Moderate (-)	Moderate (-)	Low (+/nil)	Very Low (+)	Moderate (-)	Moderate (-)	Moderate
A2 2100	High (-)	High (-)	High (-)	Moderate (+/-)	Very Low (+)	High (-)	Moderate (-)	High

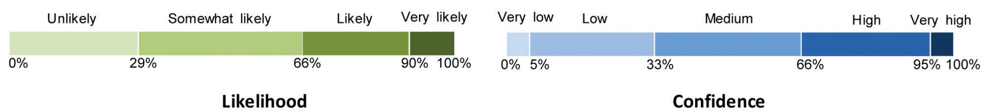


Figure 4-8 Summary of the projected effects of climate change variables on mangrove and seagrass habitats in the tropical Pacific for the B1 and A2 emissions scenarios in 2035, together with an assessment of the overall vulnerability of mangrove and seagrass habitats by integrating these effects. The likelihood and confidence associated with the integrated vulnerability assessments are also indicated. Note that the projected effects of each climate change variable can be negative (–) or positive (+); nil = no projected effect. (From Waycott et al., 2011.)

Impacts to freshwater and terrestrial ecosystems

In order to understand the potential future impacts of climate change on insular Pacific freshwater and terrestrial ecosystems, it is important to keep in mind differences between high islands with significant elevation gradients versus low islands with little or no elevation gradients, and leeward areas that receive less rainfall with more seasonal extremes versus wetter windward areas. It is also important to consider the presence and severity of other ecosystem stressors, such as invasive species, as well as resource availability and adaptive capacity. In the near term, maximizing native ecosystem resilience through intensive management of current anthropogenic stressors, especially invasive species, is critical for longer-term adaptation to climate change.

Low island ecosystems

Of critical concern is that SLR will eventually contribute to the overwash and submersion of low island ecosystems, particularly atolls. Initial effects of SLR will include changes in the location, size, and shape of the atoll islands (Webb & Kench, 2010), which will affect the type and distribution of nearshore terrestrial habitats. Continued SLR will result in the submerging of relict and wave-resistant paleoreef flats, which will subject the unconsolidated sediment cover to wave impacts and accelerate the eventual overtopping of atolls (Dickenson, 2009). Projected dates for these types of impacts are dependent upon particular atoll morphology and the rates of SLR that occur or are chosen for planning. However, it is likely that these impacts are inevitable, and will occur widely between ~2050 and 2150 (Dickinson, 2009). Terrestrial atoll ecosystems will require adaptive planning efforts well in advance for resident and migratory species dependent on these increasingly rare habitats.

Low islands are currently subjected to periodic high-wave events such as the two events recorded at Midway, Laysan, and Kure Atolls, in the NWHI, in January and February 2011. These storm-generated high-wave events were followed by the Tohoku Tsunami in March. Over the course of these events, Laysan albatross and blackfooted albatross populations lost 38% (254,000) and 45% (30,000), respectively, of their annual nests throughout the entire nesting range of these bird species (Flint et al., 2011; over 95% of nesting for each of these albatross occurs in the NWHI). With rising sea level, atoll inundation and overwash will become more frequent and will have substantial negative impacts on populations of atoll plants and animals, including the six endemic atoll terrestrial birds and plants identified in the region. Impacts include direct mortality as well as loss and/or alteration of habitat. Freshwater and brackish water wetlands will also become more saline with increasing seawater inundation and intrusion into shallow water tables. This increased salinity will impact the plants and animals that currently rely on these freshwater resources.

High island freshwater wetland and stream ecosystems

High island coastal wetlands will become more saline over time with increased inundation from high-wave events for those nearest to the shore. Unlike low island wetlands, high island wetlands have the potential to shift locations, given a sufficiently large landscape with an elevation gradient. As sea level rises, the freshwater subterranean lens of the high island will also rise, creating new freshwater wetlands at the new locations on the landscape. The extent to which coastal wetlands are lost or gained in the Pacific Islands will depend, in part, on local geomorphology, sediment supply, and existing human habitation.

As discussed in detail in Chapter 2, decreasing rainfall is associated with decreasing stream base flow (Oki, 2004), which in turn has significant impacts on habitat availability for stream-dwelling organisms (Gingerich & Wolff, 2005; Oki et al., 2010). Generally speaking, the range of streamflow conditions will shift toward less consistent flow. For example, stream systems that currently flow year-round from headwaters to the sea may become hyporheic (flow underground) in some sections during the dry season: water will percolate through the streambed but will not flow over the land surface. Also, the flow of some currently perennial streams may become seasonally dependent or otherwise intermittent, and some already intermittent streams may eventually cease to show any surface flow. This overall decline in flow will reduce turbulent stream habitats and may increase pool habitats; the species that occupy the former may give way to those who favor the latter. Decrease in streamflow also reduces overall invertebrate biomass, interrupts movement of native species along streams, and may prevent amphidromous species from re-occupying the streams where they complete their life cycle (Gingerich & Wolff, 2005; Kinzie et al., 2006). While the effect of decreasing rainfall on stream ecosystems is clearly understood, the impact of a change in the frequency of heavy rainfall events is still uncertain. In fact, an increase in these events may actually benefit native stream fauna by flushing invasive fish species to lower reaches of the streams or out to sea. Unlike the invasive stream fishes in the Pacific Islands, native freshwater fishes (gobies) are adapted to resist these flushing events or to use them as part of their natural spawning cycle (Keith, 2003).

High island alpine and subalpine ecosystems (Hawai'i only)

In the Pacific Island region, alpine and subalpine ecosystems are found only in Hawai'i and represent some of the most fragile and unique ecosystems on Earth. The harsh environment of high elevation and the natural barrier provided by lava fields has largely but not entirely spared these ecosystems from alien species invasions (Denslow, 2003). Like low islands, these alpine and subalpine areas may serve as early indicators of climate change in the Pacific Islands. Snowfall and temperature on Mauna Kea and Mauna Loa may also show changes due to global warming, which could affect the distribution and abundance of native and invasive species at these high elevations. For instance, *wēkiu* bugs (*Nysius wekiuicola*) live up to the highest elevations on both mountains and rely on insects blown up from lower elevations and immobilized or killed by the frigid temperatures they encounter (Eiben & Rubinoff, 2010). Changes in snowfall could impact the distribution and abundance of *wēkiu* (Eiben & Rubinoff, 2010). Currently, cold, high-elevation temperatures protect Mauna Kea and Mauna Loa from many invasive species. Warming at high elevations could facilitate upslope movement of invasive species on these mountains (Eiben & Rubinoff, 2010).

Hawaiian alpine ecosystems are already beginning to show strong signs of increased drought and warmer temperatures, apparently related to increasing persistence of the trade wind inversion (Cao et al., 2007) since the 1990s. The most studied biological indicator in this ecosystem is the Haleakalā silversword, *Argyroxyphium sandwicense* ssp. *macrocephalum* (Asteraceae). It is found only at high elevation (2,100 to 3,055 m [6,900 to 10,000 feet]) on the Haleakalā volcano on the Hawaiian island of Maui, where it grows for 20 to 90 years before the single reproductive event at the end of its life. After a precipitous decline to about 4,000 individuals in the early 1900s due to ungulate browsing and human vandalism, protection within Haleakalā National Park allowed it to recover to more than 50,000 individuals. Monitoring since 1982 (Loope & Crivellone, 1986) has documented a severe decline in plant numbers over the past two decades (Krushelnycky et al., 2011), apparently unrelated to effects of invasive species but happening in the same time frame as a documented increase in temperature and decrease in precipitation (as discussed in detail in the earlier chapters of this report). Recruitment of seedlings has almost ceased, and small to medium-sized plants are frequently dying without flowering, especially at the lower elevations of its range. The monitoring network was expanded substantially in 2010 to enable a more comprehensive assessment. Accurately documenting the silversword story may have potential for enhancing scientific and public understanding of what climate change has in store for Hawaiʻi.

High island wet, mesic, and dry forest ecosystems

Terrestrial forest ecosystems support the great majority of terrestrial Pacific Island biodiversity, yet most of these forest ecosystems remain largely unstudied, especially in American Sāmoa, the Mariana Islands, and the freely associated States. Initial bioclimate modeling of potential future plant distributions in Hawaiʻi, based on climate change projections of temperature and precipitation, has shown that by 2100 climate change may result in new, coastal low-elevation growth conditions that have never before occurred in the main (high) Hawaiian Islands (Price et al., 2009). Most of these new, non-analog, ecosystems will occur in areas that are already dominated by invasive species that are not native to Hawaiʻi. At higher elevations near the summit of the mountains on each of the main islands (and below the alpine/subalpine zones on Maui and Hawaiʻi), the same bioclimate modeling (Price et al., 2009) shows that wet native ecosystems that currently and naturally occupy limited areas will no longer exist by 2100. The implications for native plant species found only in these ecosystems include contraction of their ranges in part or in whole, which may contribute to the extinction of the most vulnerable species. An initial analysis of the potential bioclimatic range in 2100 of Hawaiian plants indicates that some species will experience a contraction of their bioclimatic envelope, up to and including its elimination, while others will experience no significant change or an expansion of the envelope (Figure 4-9) (Price et al., 2009).

Of great concern is the climate change response of invasive plants, animals, and diseases and their interaction with the native species of the Pacific Islands. As ecosystems are created, are lost, or shift in location and area, the potential for expansion of invasive species exists, especially if increased fire risk associated with the expansion of alien grasses (Litton et al., 2006; Varga & Asner, 2008) accompanies climate change. The potential impact of disease on native species has been characterized for avian malaria and Hawaiian forest birds. Climate change threatens to greatly expand the range of mosquitoes that transmit avian malaria and also increase the viability of the malaria parasite at high elevations (Benning et al., 2002; Atkinson & LaPointe, 2009a).

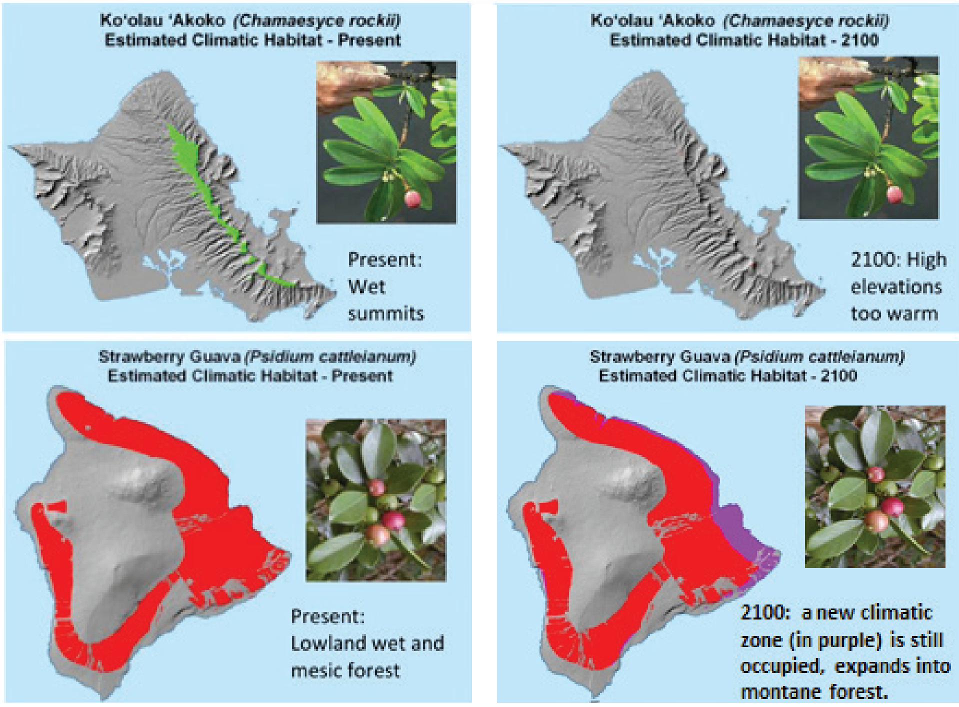


Figure 4-9 Climate-induced changes in the bioclimate envelope of plant species in Hawai'i. The bioclimate envelope of the Hawaiian endemic *`akoko* (*Chamaesyce rockii*) is projected to become greatly reduced in area and fragmented into two isolated locations. In contrast, the bioclimate envelope of the alien and invasive strawberry guava (*Psidium cattleianum*) is expected to expand into the montane forest and also occupy the new lowland climate zone produced by climate change (From Price et al., 2009.)

Implications of climate change for management

The importance of effective management of marine, freshwater, and terrestrial ecosystems cannot be overemphasized, but neither can reduction in greenhouse gas (GHG) emissions. Ultimately, without substantial reductions in GHG emissions, management actions will only succeed to a limited degree, and marine, freshwater, and terrestrial ecosystems in the Pacific Islands will be highly altered by climate change and ongoing human-induced effects. Dramatic examples of these impacts already exist in both the marine and terrestrial ecosystems of the Pacific. Figure 4-10 illustrates that, for coral reefs, strong management could result in a much better outcome for reefs under a scenario where we strongly reduce GHG emissions, but without reduced emissions, no amount of effective management will result in reefs, as they currently exist, in the future. Modeling efforts to better understand the interactions between ecological and hydrodynamic processes and human impacts for the Great Barrier Reef in Australia (Wolanski et al., 2004; Wolanski & De'ath, 2005) combined with varying management and GHG emission reduction scenarios (Richmond & Wolanski, 2011) support this conclusion. The bottom line is that while management activities to reduce local stressors can increase resilience, slow the effects of climate change, and buy time for vulnerable ecosystems, the only scenario that results in the recovery of key marine, freshwater, and terrestrial ecosystems in the Pacific Islands is one that combines effective local management and a global reduction in GHGs.

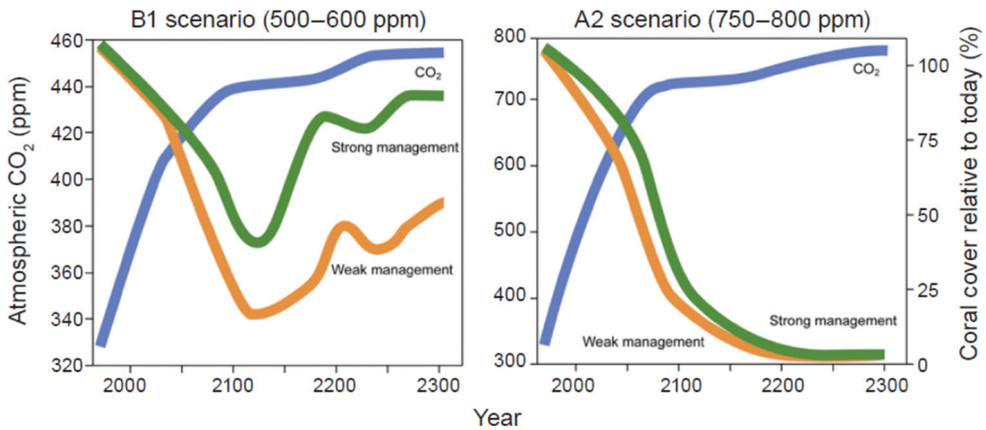


Figure 4-10 Indicative potential changes in CO_2 and coral cover over the next three centuries in a world that strongly reduces greenhouse emissions under the B1 scenario (left panel) or does not and follows the A2 scenario (right panel). The orange lines indicate likely changes to the percentage of coral cover for reefs if they are managed poorly. Green lines depict how coral cover is expected to change where strong policies and actions to manage and reduce local threats are implemented. (From Hoegh-Guldberg et al. [2011] by permission of CSIRO Publishing.)

Summary

Sound scientific information to inform management decisions in the face of climate change is needed, but there are some key challenges to providing this needed information for the Pacific Islands region. These are summarized below for marine, freshwater, and terrestrial ecosystems.

- **High quality, long-term ecological and climate monitoring with adequate spatial coverage:** Understanding the changes that Pacific Islanders are experiencing, and will experience in the future, requires consistent ecological monitoring and observations. Given the expense of long-term monitoring and considering ever-tightening budgets, the number of stations is declining. In addition, the continued reduction of long-term environmental (climate) monitoring efforts degrades the validation and refinement of modeling and downscaling approaches. Such degradation critically endangers not only our ability to accurately understand the magnitude of change that is happening, but also our ability to identify, forecast, and respond to extreme environmental conditions that may cause irreparable damage to ecosystems and the communities/economies that depend upon them.

- **Terrestrial and aquatic research sites across the region:** A major observation of this assessment is the lack of adequate ecosystem-monitoring long-term study sites throughout the Pacific Islands. If climate change impacts on freshwater and terrestrial ecosystems are to be effectively assessed in the Pacific Islands, a well-designed ecological program is needed. Currently, studies on the long-term stability and biodiversity of terrestrial and aquatic ecosystems are conducted only in limited locations in Hawaiʻi. Additional study sites are needed throughout the Pacific Islands.
- **Downscaled models for the Pacific Islands:** One of the challenges of the Pacific Islands is that many of the global climate models (GCMs) are not adequate for the region. Downscaling of global models, taking into consideration the regional and local phenomena that influence the regional climate system, needs to be done (for further summary of modeling efforts, see Appendix B of this report). Alternatively, nesting regional climate models into future GCM runs is a viable alternative to post-GCM downscaling. This would provide much more comprehensive capture of air-sea fluxes and boundary-layer conditions than traditional downscaling approaches.
- **Integrated biogeochemical and physical models:** Biological responses to a changing climate can have cascading and interactive effects that we cannot predict. Consequently, direct impacts to one organism will affect many other organisms in the system. Integrating biogeochemical and physical models will provide a better understanding of overall impacts.
- **Ocean acidification research:** Ocean acidification is a well-understood chemical process, but the impacts of the changing carbonate chemistry on key organisms such as larval fish, coral reefs, phytoplankton, other zooplankton, larvae of amphidromous (freshwater adults with marine larval stages) species, and other calcifying organisms are not. Research to better understand the biological response is necessary to understand and prepare for these potentially far-reaching impacts.
- **Resilience of key ecosystems and dependent communities:** The combined effects of climate change and anthropogenic stressors (e.g., the introduction of invasive species, land-use practices, land-based sources of pollution, fishing practices, and so forth) are often synergistic, with dire consequences for native ecosystems. Reducing human-caused stresses on marine, freshwater, and terrestrial ecosystems is a critical part of maintaining and restoring their resilience. Improved control and management of invasive species, along with steps toward better prevention of their introduction to native ecosystems, are necessary to achieve this goal.

Key Findings for Marine, Aquatic, and Terrestrial Ecosystems

- Surface air temperature has risen over the Pacific Islands region over the last century. This warming is spatially and temporally variable, with more warming at higher elevations and at night. Minimum and maximum temperatures and the frequency and intensity of days of extreme heat are projected to increase across the region.

- Warming at high elevations could exacerbate invasive species problems and alter the distribution of native species in high island ecosystems.
- Average sea-surface temperature across the region has risen over the last century, with more rapid warming since the 1970s. Surface temperatures across the region are projected to increase at levels that will impact key marine ecosystems.
- Increased sea-surface temperatures are correlated with increased frequency and intensity of mass coral bleaching events and associated mortality in the region. The distribution of phytoplankton and key fisheries species is also projected to change with changes in sea-surface temperature, currents, and wind patterns.
- Changes in precipitation patterns may lead to increased coastal erosion, decreases in coastal water quality, and changes in terrestrial and aquatic species distribution.
- Sea level in the region has risen at a rate greater than the global average. Sea level is projected to continue to rise, and regional fluctuations at inter-annual to multidecadal time scales will superimpose on global sea-level rise.
- Sea-level rise is of critical concern to low-lying atolls where overwash and inundation will contribute to loss of terrestrial ecosystems. Key habitats such as mangroves and coastal wetlands could also be negatively impacted by erosion and inundation.
- CO_2 is absorbed by sea-water, resulting in a series of chemical reactions that reduce the sea-water pH, carbonate ion concentration, and the availability of the biologically important calcium carbonate minerals calcite and aragonite through a process known as ocean acidification.
- The biological impacts of ocean acidification to key organisms, including larval fish, coral reefs, phytoplankton, zooplankton, and other calcifying organisms, are thought to have potentially devastating effects and must be better understood to prepare for these potentially far-reaching impacts.
- For sensitive ecosystems like coral reefs, with high vulnerability and potentially low adaptive capacity, greenhouse gas reduction is the only meaningful response. High levels of local protection will only buy time for these ecosystems and do not provide immunity to significant climate change impacts.
- Projected increase in tropical cyclone intensity could impact the geomorphology of islands and result in habitat destruction of terrestrial ecosystems (forests) and marine ecosystems (coral reefs, seagrasses, and mangroves), influencing the spread of invasive species and reducing shoreline protection for coastal communities.

FOCUS ON IMPACTS

Case Study 4-1

Climate change threatens Hawaiian forest birds

In Hawai'i, geographic isolation has prevented the natural establishment of mammals, terrestrial reptiles, amphibians, and many insect species, such as biting mosquitoes. Isolation has also facilitated the spectacular evolutionary radiation of Hawaiian honeycreepers from a single small flock of North American finches into more than 50 species and subspecies of endemic forest birds (Pratt, 2009).

With the arrival of humans came the clearing of forests and the introduction of non-native species and their diseases. More than 40 mosquito species have been captured in Hawai'i, and six have become established, most recently in 2004 (LaPonte & Burgett, 2005). The southern house mosquito was the first to arrive in Hawai'i in 1826 (Atkinson & LaPointe, 2009b). It is the vector for avian malaria and avian pox. The malaria parasite arrived later with the introduction of non-native birds, probably around 1871. These introduced birds are the perfect avian malaria host: they show no signs of infection and remain infectious for long periods of time.

Case Study 4-1 Photo 1 The '*Apapane* honeycreeper, seen here at Hawai'i Volcanoes National Park, is one of the only remaining, relatively abundant species of Hawaiian honeycreepers. (Courtesy of Simon Bisson.)

Habitat loss, predation, and competition have taken their toll on Hawaiian honeycreepers, but this trio of invasive species—alien birds, malaria, and mosquitoes—were, and still are, a major threat to the honeycreepers' long-term survival. Almost all of these birds are vulnerable to avian malaria, with mortality rates as high as 65% to 90% after being bitten by a single infective mosquito (Atkinson & LaPointe, 2009a, 2009b). Of the 50 species and sub-species of endemic Hawaiian honeycreepers, only 22 have survived the combined effects of habitat loss, disease, predation, and competition from alien species. The most recent victim, the *Po'ouli*, became extinct in 2004 (Pratt, 2009).

Mosquitoes and avian malaria do not do well in Hawai'i's cooler high elevations. Below 13° C (about 55° F), the malaria parasite cannot complete its maturation cycle, so the disease cannot be transmitted. In addition, the southern house mosquito, which transmits avian malaria, is active at night when temperatures are cooler. Consequently, the prevalence of avian malaria in native forest birds is low above 1,500 m (about 5,000 feet) (Atkinson & LaPointe, 2009a). At lower elevations, mosquitoes and malaria are abundant, and most honeycreepers can no longer survive in the warm mesic and wet forests that were once ideal habitats. Hawai'i's cool, high mesic and wet forests have become their last refuge. But today, climate change threatens to open up these refuges to avian malaria.

As climate change warms the air, the range of mosquitoes will expand upslope, and infective malaria parasites will develop at high elevations. Currently, at higher elevations, avian malaria transmission is seasonal, occurring during the warm summer and fall when mosquito populations are at a maximum. Thus, the cooler winter months and night temperatures are critical to the survival of honeycreepers.

As global warming raises air temperatures, their seasonal high elevation refuge will shrink and eventually disappear (Figure 4-11) (Benning et al., 2002; Atkinson & LaPointe, 2009a). It is likely that the spread of mosquitoes and avian malaria (as well as avian pox) into the high elevations of Hawai'i will eventually lead to the extinction of many, perhaps all, of the honeycreepers that currently survive in these areas.

Current temperatures at high elevations in Hawai`i have risen about 0.26° C per decade averaged over the day and night. But of greater concern is the rise in nighttime temperatures, when the southern house mosquito is most active. These have risen about 0.44° C (0.79 °F) per decade since 1975 (Giambelluca et al., 2008). As a result, the

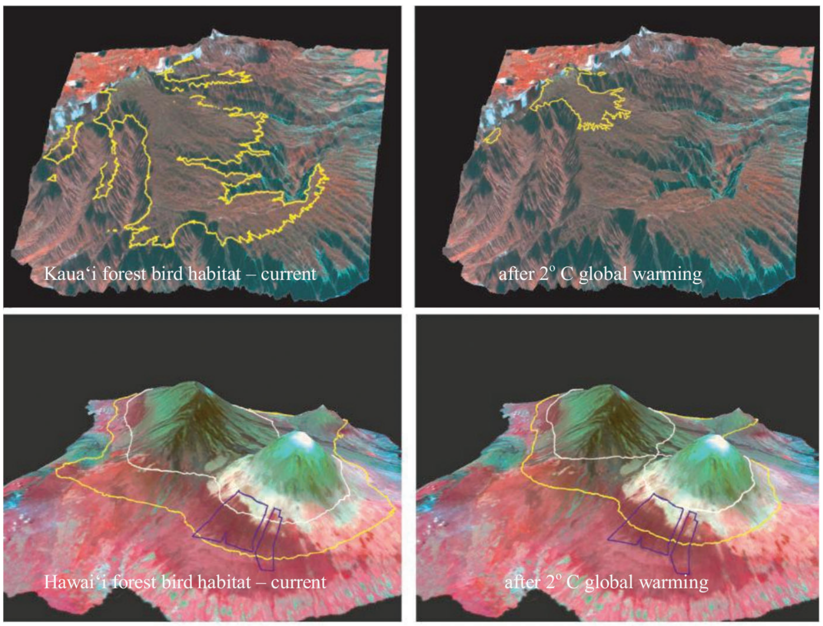


Figure 4-11 Projected changes in the location of the forest cover in relation to 17°C (yellow) and 13°C (white) isotherms under current conditions and with a 2°C warming of the climate. Changes are shown for Hakalau Forest National Wildlife Refuge (blue boundary) on Hawai'i, and the Alakai swamp region on the island of Kaua'i. (From Benning et al., 2002.)

prevalence of avian malaria in Hawaiian forest birds at Hakalau Forest National Wildlife Refuge (1,500 to 2,000 m; 5,000 to 6,500 feet elevation) on the island of Hawai'i has risen from 2.1% to 5.4% over the past decade (Freed et al., 2005). The prevalence of avian malaria at high elevations on Kaua'i has risen as much as 30% over the past decade (Atkinson & Utzurrum, 2010).

High-elevation forest restoration is needed to expand the upward range available to these forest birds. This will require addressing long-standing problems with invasive plants and animals. And there is hope for some Hawai'i honeycreepers. Natural resistance to avian malaria has developed in one species, the *Hawai'i amakihi,* which is now more abundant in low-elevation forests with high levels of mosquitoes and avian malaria than at disease-free high-elevation sites (Woodworth et al., 2005; Kilpatrick et al., 2006). The hope is that good habitat management can help other honeycreepers develop resistance to avian malaria (Kilpatrick, 2006). Unfortunately, the rate of warming in Hawai'i may not give these birds enough time to develop resistance. Without human assistance, global warming combined with avian malaria may overwhelm Hawaiian honeycreepers and other forest bird species.

FOCUS ON IMPACTS

Case Study 4-2

Fish populations respond to climate conditions

Fishing is a way of life in the Pacific Islands. Subsistence fishers ply the waters of every inhabited shore as well as many uninhabited ones; seafood consumption is high, providing a primary protein source; and fishing is prominent in cultural traditions. There are many stories, chants, and songs about fish and fishing throughout the Pacific region. In Polynesia, the most famous perhaps are those of Maui and his legendary fishing hook.

Oh the great fish hook of Maui!
Manai-i-ka-lani ' made fast to the heavens' its name;
An earth-twisted cord ties the hook.
Engulfed from the lofty Ka'uiki.
Its bait the red billed 'Alae,
The bird made sacred to Hina.
It sinks far down to Hawai'i,
Struggling and painfully dying.
Caught is the land under the water,
Floated up, up to the surface,
But Hina hid a wing of the bird
And broke the land under the water.
Below, was the bait snatched away
And eaten at once by the fishes,
The Ulua of the deep muddy places.

"Chant of Kuali'i," ca. 1700 AD
(Westervelt, 1910)

Case Study 4-2 Photo 1 Fish hook collection, Bishop Museum, Honolulu, Hawai'i. (© 2008 Debbi Long, "hooked," used under a Creative Commons Attribution-NonCommercial-ShareAlike license.)

In addition to their importance to traditional practices and food security for island communities, open-ocean fish populations in the Pacific play an increasingly dominant role in global fish production. The Western Pacific Regional Fishery Management Council estimates the annual catch of skipjack tuna (*Katsuwonus pelamis)*, yellowfin tuna (*Thunnus albacares)*, bigeye tuna (*T. obesus),* and South Pacific albacore tuna (*T. alalunga*) at about 2.7 million metric tonnes. These tuna species are highly migratory and range throughout the Pacific, and adults tolerate a relatively wide range of conditions (Brill, 1994). Yet, climatic conditions greatly influence the productivity and geographic range of Pacific tuna populations (Miller, 2007).

Tuna have been shown to respond to El Niño-Southern Oscillation (ENSO) events. Sea-surface temperature influences tuna productivity and optimal development through different life stages (Lehodey et al., 1997; Lehodey, 2001; Lu et al., 2001). ENSO-related shifts create a disadvantage for local fishers who, unlike large-scale commercial fleets, cannot follow the tuna to more productive waters thousands of miles away.

Due to projected ocean warming and other climate-associated changes in marine ecosystem productivity, it is projected that over the 21st century, tuna distributions "are likely to shift progressively towards the central and eastern Pacific" (Bell et al., 2011) (Figure 4-12). Currently, in the Western North Pacific sub-region, the domestic tuna fisheries of the Federated States of Micronesia and the Republic of the Marshall Islands are valued at $2.67 million and $2.44 million annually, respectively (Bell et al., 2011). The contribution of tuna fisheries to these economies may well lessen as the projected shift in populations takes place.

The complexity of marine ecosystems makes it difficult to predict how climate change will alter discrete "strands" of the food web upon which tuna and other large pelagic fish depend. There are indications that, in addition to changes in sea-surface temperature, changes in ocean circulation and ocean chemistry will heavily influence productivity throughout the region (Le Borgne et al., 2011; Polovina et al., 2011). By the end of this century, the total primary production and fish catch is projected to increase by 26% in the subtropics and decrease by 38% and 15% in the temperate and the equatorial zones, respectively (Polovina et al., 2011). This projected decrease, in combination with shifting fish populations, may have a significant and unequal economic impact on Pacific Island sub-regions. One cannot place a monetary value, however, on how these projected changes in pelagic fisheries will impact the Pacific Island way of life.

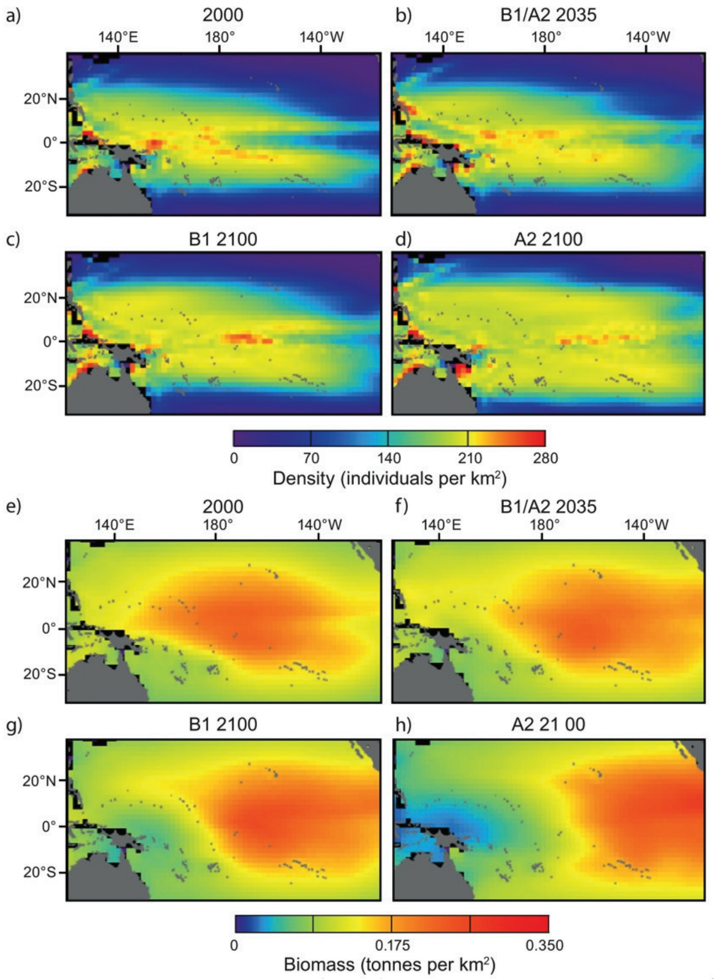


Figure 4-12 Projected distributions (density) for skipjack tuna larvae recruits from the SEAPODYM model (a) in 2000; (b) under the B1/A2 emissions scenario in 2035; (c) under B1 in 2100; and (d) under A2 in 2100. Also shown are estimates of total biomass (tonnes per square kilometer) of skipjack tuna populations based on average (1980–2000) fishing effort in (e) 2000; (f) under B1/A2 in 2035; (g) under B1 in 2100; and (h) under A2 in 2100. (From Lehodey et al., 2011.)

FOCUS ON ADAPTATION

Case Study 4-3

Pacific coral reef management in a changing climate

Tropical coral reefs are among the most productive and diverse ecosystems in the world: thousands of species coexist in a complex structure built by living corals. Coral ecosystems are of particular ecological, economic, and cultural importance in the Pacific Islands region, and this region supports the majority of coral reefs within the United States' jurisdiction.

These ecosystems are declining due to a plethora of human impacts, including overutilization, land-based pollutants, introduced invasive aquatic species, and climate change. Two climate-related phenomena in conjunction pose a potentially catastrophic threat to the long-term survival of coral reef ecosystems in the Pacific Islands region: rising sea-surface temperatures (SSTs) and changes in ocean chemistry.

Over the past 30 years, periods of elevated SST have become more commonplace, often correlating with coral bleaching (Donner, 2011). Coral bleaching occurs when water temperatures rise 1° to 2°C (1.8° to 3.6°F) above the warmest normal summer temperatures and persist over three to four weeks or more. This stress can cause the corals to expel their crucial, colorful symbiotic algae and thus turn white (hence the name

Case Study 4-3 Photo 1 A healthy tropical Pacific coral reef, Palmyra Atoll National Wildlife Refuge. (Courtesy of J. Maragos, USFWS.)

"bleaching"). Intense coral bleaching is often followed by coral death, though corals can recover from mild bleaching events.

Coral bleaching is becoming more frequent as the oceans warm (Hoegh-Guldberg, 1999). Coral bleaching in 1998 and 2010 caused large-scale coral deaths in reef systems around the globe, with the 1998 event heavily impacting Palau in the Western North Pacific sub-region, and Palmyra Atoll in the Central North Pacific sub-region (Turgeon et al., 2002). In the Republic of Palau, nearly one-half (48%) of 946 surveyed colonies were totally bleached, and a further 15% were partially bleached (Bruno et al., 2001). Coral bleaching has also been observed elsewhere in the Micronesian, Marianas, Samoan, and Hawaiian archipelagos. The *Reefs at Risk Revisited* report (Burke et al., 2011) predicts that by 2050 many of the reefs in the Pacific will bleach annually. This frequency of bleaching is worrying because it allows little time for corals to recover. Annual summer bleaching has already been reported from American Sāmoa (Fenner & Heron, 2008).

Adding to the stress of high temperatures is the increasing acidification of the ocean, caused by rising levels of carbon dioxide in the air that is absorbed by sea water. One of the impacts of ocean acidification is that less carbonate is available in the form necessary for coral reefs to build their calcium carbonate skeletons. The skeletons that these small coral polyps build are a fundamental building block of coral reef ecosystems. Based on the rate of coral loss reported over the past 20 years, and the projected effects of more frequent coral bleaching and ocean acidification, average coral cover throughout the Pacific is expected to decline to 15% to 35% by 2035 compared with 20% to 40% in 2007 (Bruno & Selig, 2007; Hoegh-Guldberg et al., 2011).

Coral reef managers have few options for preventing or reducing coral bleaching because it is not possible to cool large masses of sea water. They can focus on increasing the potential resilience of reefs by reducing human impacts such as overfishing, sediment and pollutant runoff, and invasive species. In addition, early-warning systems that predict coral bleaching and monitor the effects on reef ecosystems have made it possible to identify which reefs are perhaps more resistant to bleaching and have a better chance of recovery.

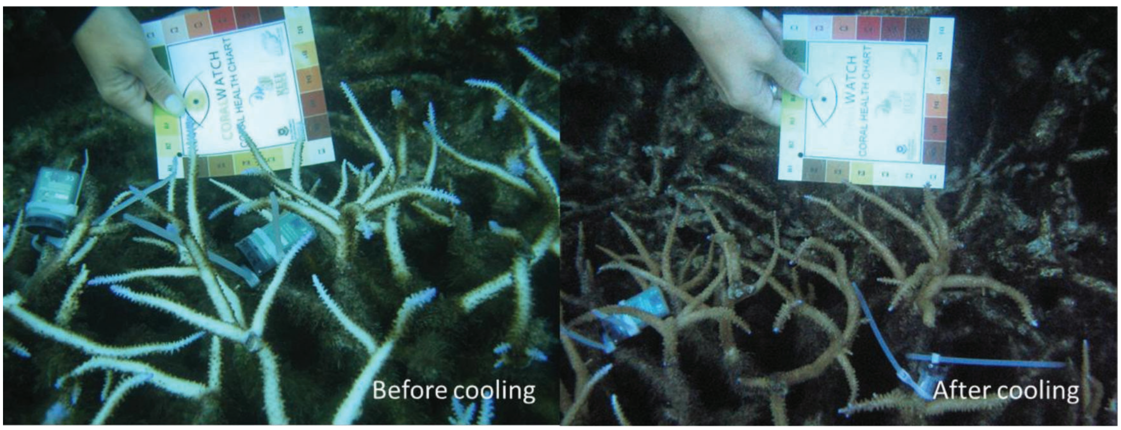


Figure 4-13 Bleached *Acropora* corals before (left) and after (right) treatment with cooled seawater for 24 hours, Tutuila, American Samōa. (Courtesy of B. Von Herzen, Climate Foundation.)

In an effort to expand the range of management options, researchers in American Sāmoa are testing technologies that could cool selected, important reefs and shade them from strong sunlight. Seasonally high temperatures at a particular reef on the island of Tutuila cause predictable coral bleaching (Fenner & Heron, 2008), creating an ideal test site. Initial tests have shown that reducing peak water temperatures by about 1.0°C (1.8°F) enables two sensitive species of coral to regain and retain their healthy color during periods of thermal stress (Figure 4-13). In a second set of experiments, shading was found to restore healthy color in bleached coral. In conjunction with strategies for reducing land-based stress, these and other management tools may provide Pacific Island communities with new, localized conservation measures to help combat the effects of global climate change on their valuable coral reef resources.

Chapter 5

Conclusions

The Pacific Islands region is experiencing climate change. Key indicators of the changing climate include rising carbon dioxide in the atmosphere, rising air and sea-surface temperatures, rising sea levels and upper-ocean heat content, changing ocean chemistry and increasing ocean acidity, changing rainfall patterns, decreasing base flow in streams, changing wind and wave patterns, changing extremes, and changing habitats and species distributions.

These climatic changes pose enormous challenges for the region. Key findings of this assessment suggest multiple concerns for human and natural communities:

- Low islands, coral reefs, nearshore and coastal areas on high islands, and high-elevation ecosystems are most vulnerable to climatic changes.
- Freshwater supplies will be more limited on many Pacific Islands, especially low islands, as the quantity and quality of water in aquifers and surface catchments change in response to warmer, drier conditions coupled with increased occurrences of saltwater intrusion.
- Rising sea levels will increase the likelihood of coastal flooding and erosion, damaging coastal infrastructure and agriculture, negatively impacting tourism, reducing habitat for endangered species, and threatening shallow reef systems.
- Extreme water levels will occur when sea-level rise related to longer-term climate change combines with seasonal high tides, inter-annual and interdecadal sea-level variations (e.g., ENSO, Pacific Decadal Oscillation, mesoscale eddy events), and surge and/or high runup associated with storms.
- Higher sea-surface temperatures will increase coral bleaching, leading to a change in coral species composition, coral disease, coral death, and habitat loss.
- Rising ocean acidification and changing carbonate chemistry will have negative consequences for the insular and pelagic marine ecosystems; although potentially dramatic, the exact nature of the consequences is not yet clear.
- Distribution patterns of coastal and ocean fisheries will be altered, with potential for increased catches in some areas and decreased catches in other areas, but with open-ocean fisheries being affected negatively overall in the long term.
- Increasing temperatures and, in some areas, reduced rainfall will stress native Pacific Island plant and animal populations and species, especially in high-elevation ecosystems, with increased exposure to non-native biological invasions and fire, and with extinctions a likely result.
- Threats to traditional lifestyles of indigenous communities in the region

(including destruction of coastal artifacts and structures, reduced availability of traditional food sources and subsistence fisheries, and loss of the land base that supports Pacific Island cultures) will make it increasingly difficult for Pacific Island cultures to sustain their connection with a defined place and their unique set of customs, beliefs, and languages.
- Mounting threats to food and water security, infrastructure, and public health and safety will lead increasingly to human migration from low islands to high islands and continental sites.

This assessment also highlights the following:

- The high interannual and interdecadal variability of the climate in the Pacific Islands region (e.g., ENSO, Pacific Decadal Oscillation) makes it difficult to discern long-term trends from short-term data.
- Many Pacific Islands lack long-term, high-quality data on rainfall, streamflows, waves, and ecosystems, and continued monitoring is needed.
- Global circulation models need to be downscaled to provide higher-resolution projections for Pacific Islands to account for the influence of local topography on weather patterns and the potential impact of climate change on ecosystems.
- Sea level in the Western North Pacific has risen dramatically starting in the 1990s. This regional change appears to be largely wind-driven, is associated with climate variability, and is not expected to persist over time.
- Some islands in the region have no human inhabitants and few human impacts, offering a relatively pristine setting in which to assess the impacts of climate change on natural settings.
- Integrated biological, geochemical, and physical models are needed to improve understanding of the pressures on ecosystems and ecological responses to climate change in the Pacific Islands region.
- A better understanding of how climate change affects invasive species and their interactions with native species is needed.
- A comprehensive evaluation of the effectiveness of alternative adaptation strategies is needed to refine planning and management decisions.
- The isolation of the Pacific Islands region from the contiguous United States (and the isolation of islands from one another) presents challenges to the regional exchange of information and limits the influence of regional leaders in national and global decision-making processes.
- The recovery of key marine, freshwater, and terrestrial ecosystems in the Pacific Islands combines effective local management and a global reduction in greenhouse gases.

Many of the impacts highlighted in this report are now unavoidable, making some degree of adaptation essential. Some jurisdictions (e.g., Hawai‘i, American Sāmoa) are more advanced than others in developing adaptation plans and policies. Several regional coordination efforts are facilitating data collection and analysis as well as access to actionable information. The diversity of natural and human communities in the region means that while regional cooperation is essential to progress efficiently with adaptation activities, a place-based approach is also important.

An informed and timely response is necessary to enhance resilience to the myriad changes already occurring and those yet to come. Additional research, a sustained assessment process, and public engagement in the development of useful information will enhance Pacific Islanders' ability to address the challenges they confront.

Advancing knowledge

Further research is needed to strengthen scientific understanding of climate change and its impacts and to inform adaptation strategies for the Pacific Islands. Ongoing research in the following areas will help to advance knowledge in the region.

Improving Data Collection

Declines in the total number of observation (measurement) stations in recent decades are a major obstacle to collecting robust data on temperature, rainfall, streamflow, sea level, winds, waves, and other variables needed to understand historic changes in physical and natural systems and to verify models of projected change. Data documenting changes in ocean chemistry and biological productivity are also sparse, and more comprehensive monitoring of shoreline changes is needed. The current lack of funding for maintaining existing monitoring networks and for developing more comprehensive and integrated observation networks across this vast region needs to be addressed urgently.

Improving Model Projections

Compared with other regions, the Pacific Islands region needs global climate models to be downscaled at a higher resolution to account for regional and local phenomena. Higher-resolution models can begin to simulate local conditions and generate new capacity for planning adaptation measures. Another important research need is analysis of the uncertainties inherent in the next generation of models. One of the greatest sources of uncertainty in climate projections is the lack of consistency in projected ENSO changes. Better quantifications of and reductions in uncertainty may come from a better understanding of natural variation associated with inter-annual and interdecadal cycles. Analyses are needed to determine also the extent to which observed changes are attributable to short-term natural variability, long-term human-induced climate change, or both.

Developing Biogeochemical and Physical Models

Research is needed to develop and test integrated biogeochemical and physical models to provide a better understanding of the pressures on ecosystems. We also need to examine how organisms and ecosystems respond to climate change. For instance, understanding how invasive species will react to climate change is important for developing effective plans to manage natural resources. Understanding the impact of changing carbonate chemistry in the ocean is needed to explain and prepare for changes in coral reefs and key marine organisms. Similarly, socio-ecological models need to reflect the dynamic interactions between human communities and the ecosystems they rely on and how these relationships are altered under different climate scenarios.

Human Responses

Research is needed on how humans will respond to climate change. For instance, analyses of changes in cultural practices and traditional resource use in response to historical climate variability may help to inform adaptation plans addressing future climate scenarios. Also needed is a comprehensive evaluation of the effectiveness of various adaptation strategies (e.g., shoreline hardening or retreat, changing agricultural practices, developing renewable energy sources, developing more comprehensive disaster management plans, migration, and so forth) to help refine planning and management decisions. Research examining the role of climate science in Pacific Islanders' responses to climate change will help to identify barriers to the use of climate information by public and private decision makers. Such research will also facilitate development of visualization tools and decision-support systems that address real-world problems.

Partnerships

Partnerships are fundamental for sustaining a regional climate assessment process and addressing the impacts of climate change across isolated and diverse islands. Key partners include stakeholders who make real-world decisions (e.g., water managers, natural resource managers, farmers, conservationists, hazards managers, urban planners, tourism developers, cultural leaders) because they can help to identify the most urgent problems and needed information. Regional networks are also key in facilitating communication, coordinating and leveraging resources, and efficiently linking stakeholders, scientists, and institutions to develop actionable information and decision-support tools. Coordinating adaptation efforts and the monitoring and reporting of the results of those efforts via regional networks will help to streamline adaptation planning. Although the jurisdictions in the region can make considerable progress with their own policies and resources, the scale of vulnerabilities and impacts suggests a strong role also for the federal government. Federal policies and resources aimed at continued climate monitoring will provide essential information for communities to use in developing and implementing adaptation plans. Federal programs that facilitate data sharing and collaborations across government agencies and between government and non-government partners will help generate integrated models and analyses that can be quickly transferred to real-world applications.

Overall, a long-term, coordinated effort is required to understand and respond adequately to the climate challenges confronting Pacific Islands and their communities. The current regional professional culture of communication and collaboration, with roots in indigenous island cultures, provides a strong foundation for this effort and will be important for building resilience in the face of the changing climate.

Appendix A

Glossaries Related to Weather and Climate in the Pacific Islands

For more in-depth definition and explanation of technical terms in this report, please see the following glossaries:

American Meteorological Society
http://amsglossary.allenpress.com/glossary/browse

Pacific Climate Change Science Program (1.5MB PDF document; glossary begins on p. 22)
http://www.cawcr.gov.au/projects/PCCSP/Nov/Vol1_RefGlossIndex.pdf

Pacific Storms Climatology Products
http://www.pacificstormsclimatology.org/index.php?page=glossary

Appendix B

Future Regional Climate: Modeling and Projections

By Kevin Hamilton

The global and basin-scale contexts for climate change projections in the Pacific

Projections of how climate elements for the insular Pacific may change under prescribed climate forcing scenarios involve a cascade of uncertainties associated with the global, regional, and local aspects. Experience with different forcing scenarios suggests that the local forced climate perturbations will typically scale roughly linearly with the global mean surface temperature warming (Christensen et al., 2007; Meehl et al., 2007) (Figures B-1 and B-2), so the uncertainties in the projections of global mean temperature are directly reflected in the local effects. Current state-of-the-art coupled global climate model (GCM) projections for the global mean temperature response of the climate to projected increases in greenhouse gas (GHG) concentration typically vary by a factor of about two. This factor of two uncertainty can be seen, for example, in a figure from the AR4 report (Figure B-3), which shows the results for 23 CMIP3 global coupled GCMs run for the 21st century under the SRESA1B scenario. The global mean warming seen in these projections is consistent with other empirical estimates of the temperature sensitivity of the global climate system, but such empirical estimates also suffer from a factor of two or more uncertainty (Knutti & Hegerl, 2008).

The tropical Pacific is notable for the large inter-annual variability of sea-surface temperature (SST), surface winds, and rainfall connected with the El Niño-Southern Oscillation (ENSO) phenomenon. Notably, the zonal gradient of SST has large variations between El Niño states (reduced equatorial SST zonal gradient and weaker Walker circulation and surface trade winds) and La Niña states (enhanced equatorial SST zonal gradient and stronger Walker circulation and surface trade winds). The large-scale ENSO variations have substantial effects on the inter-annual variations of rainfall seen in individual islands. Among the USAPI, Yap, Palau, Chuuk, Guam, and the Northern Marianas Islands all share in the anomalously dry (wet) weather on average in the western equatorial Pacific during the El Niño (La Niña) extremes of the Southern Oscillation. Hawaiʻi and Guam are located more centrally in the Pacific but also have observed correlations between seasonal rainfall and the state of ENSO—with El Niño generally being connected with anomalous dry weather in Hawaiʻi and with wet weather in Sāmoa. The significant control of seasonal rainfall over these islands by ENSO suggests that

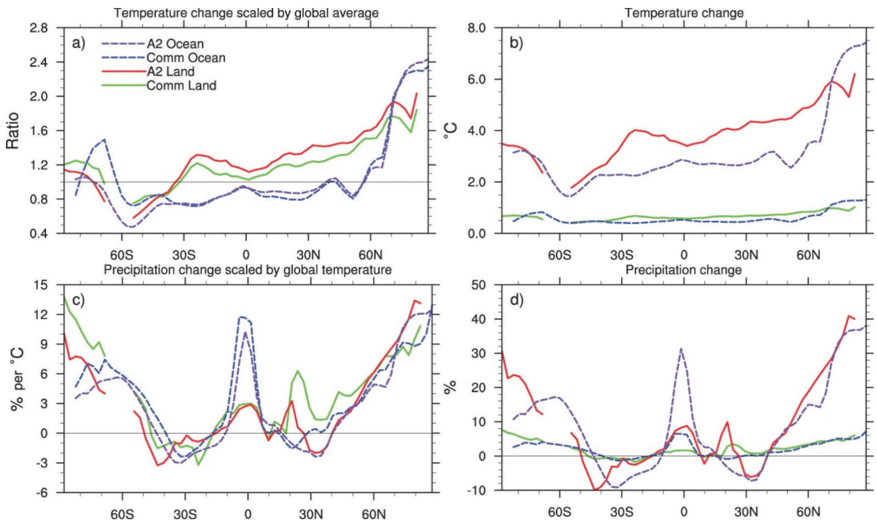


Figure B-1 The general magnitude of changes in air temperature and precipitation in the Pacific region is projected to be comparable to global estimates of average change over both land and ocean. Zonal means over land and ocean separately, for annual mean surface warming (a, b) and precipitation (c, d), shown as ratios scaled with the global mean warming (a, c) and not scaled (b, d). Multi-model mean results are shown for two scenarios, A2 and Commitment, for the period 2080–2099 relative to the zonal means for 1980–1999. (From IPCC AR4, Section 10.7, Figure 10.6; Meehl et al., 2007.)

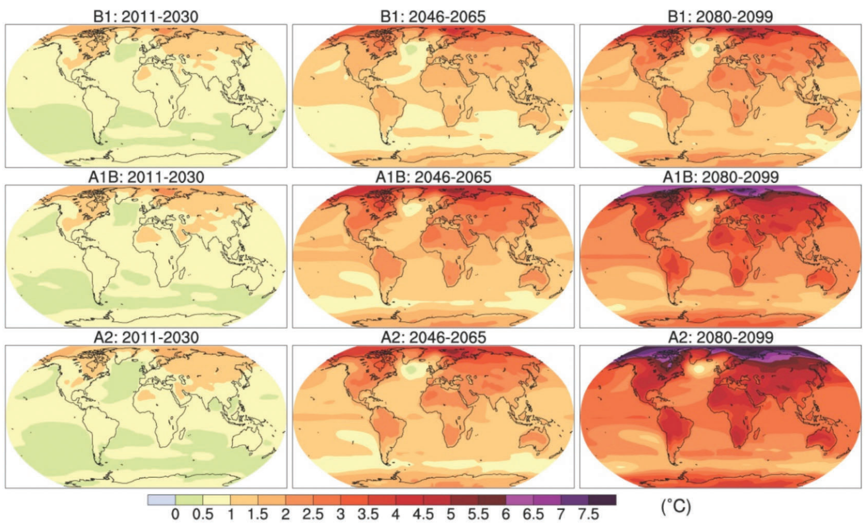


Figure B-2 Global-scale temperature patterns for three IPCC warming scenarios and time periods are shown here. In each case, greater warming over most land areas is evident. Over the ocean, warming is relatively large in the Arctic and along the equator in the eastern Pacific. Multi-model mean of annual mean surface warming (surface air temperature change, °C) for the scenarios B1 (top), A1B (middle), and A2 (bottom), and three time periods, 2011–2030 (left), 2046–2065 (middle), and 2080–2099 (right). Anomalies are relative to the average of the period 1980–1999. (From IPCC AR4, Section 10.3.2.1, Figure 10.8; Meehl et al., 2007.)

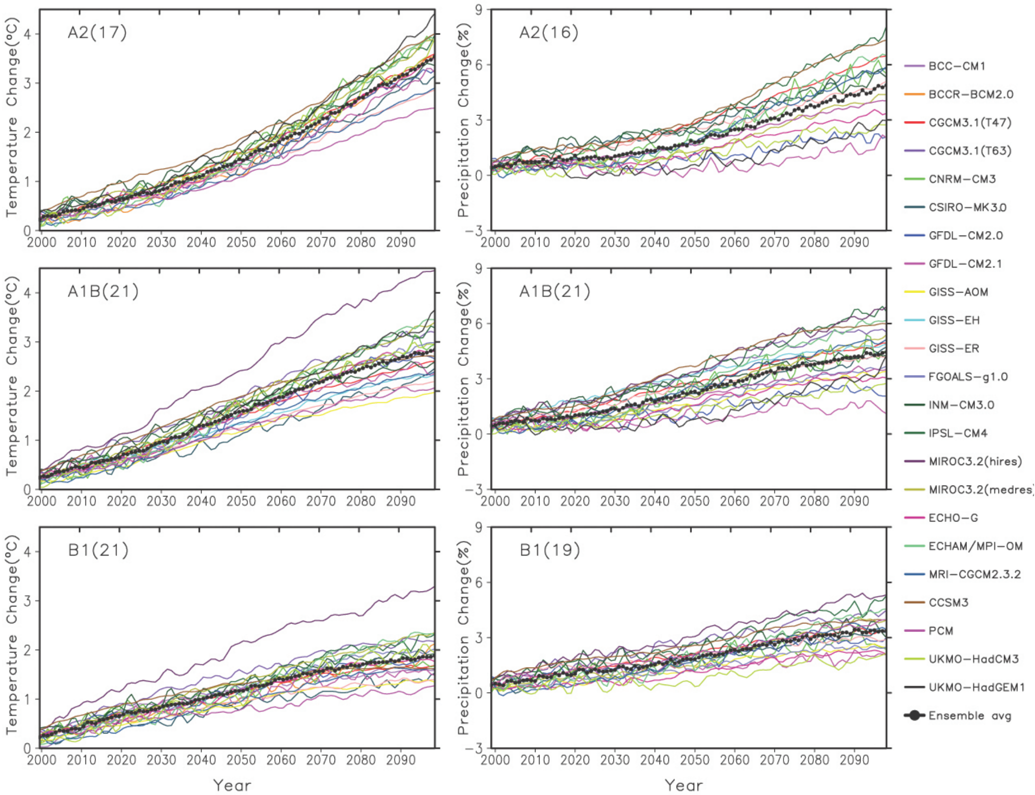


Figure B-3 Time series of globally averaged (left) surface warming (surface air temperature change, °C) and (right) precipitation change (%) from the various global coupled models for the scenarios A2 (top), A1B (middle), and B1 (bottom). Numbers in parentheses following the scenario name represent the number of simulations shown. Values are annual means, relative to the 1980–1999 average from the corresponding 20th-century simulations, with any linear trends in the corresponding control-run simulations removed. A three-point smoothing was applied. Multi-model (ensemble) mean series are marked with black dots. (From IPCC AR4, Section 10.3.1, Figure 10.5; Meehl et al., 2007.)

long-term changes in the Pacific basin–scale SST gradients and the Walker circulation will play a critical role in determining the mean rainfall changes on each of the islands.

The strong inter-annual variability in this region is thought to be a consequence of positive air-sea coupling feedbacks, and these feedbacks will also be a complicating factor in determining the mean response of the tropical Pacific circulation to climate forcing. There has been considerable work published on both analyzing the observed tropical Pacific trends in SST and atmospheric circulation over the last several decades and examining the future trends projected in global warming simulations. In the 2007 IPCC report, an ensemble of sixteen GCMs was run (Meehl et al., 2007) (Figure B-4), specifically comparing for each individual model the spatial pattern correlation of the simulated 21st-century trend in the equatorial Pacific (10S to 10N, 120E to 80W) SST with the first empirical orthogonal function (EOF) of the SST in the control run of the same model. The results for a positive (negative) correlation were interpreted as a long-term trend toward more "El Niño-like" ("La Niña-like") conditions (although note that DiNezio et al., 2009, demonstrate the limitations of trying to characterize the mean changes in the tropical Pacific as simply "El Niño-like" or "La Niña-like"). The results revealed substantial scatter among model projections, with the correlations varying between about –0.6 to +0.85, although 13 of the 16 models had positive correlations. Figure B-5 (Power & Kociuba, 2011) shows an analysis of the projected surface pressure change between the eastern and western equatorial Pacific in 21 CMIP3 models. The multi-model mean shows a weakening of the zonal gradients that would be consistent with weaker surface winds along the equator, but 6 of the 21 models have projected changes of the opposite sign to the multi-model mean.

The situation has been complicated by somewhat confusing results concerning the observed long-term trends in equatorial Pacific SST and overlying atmospheric circulation.

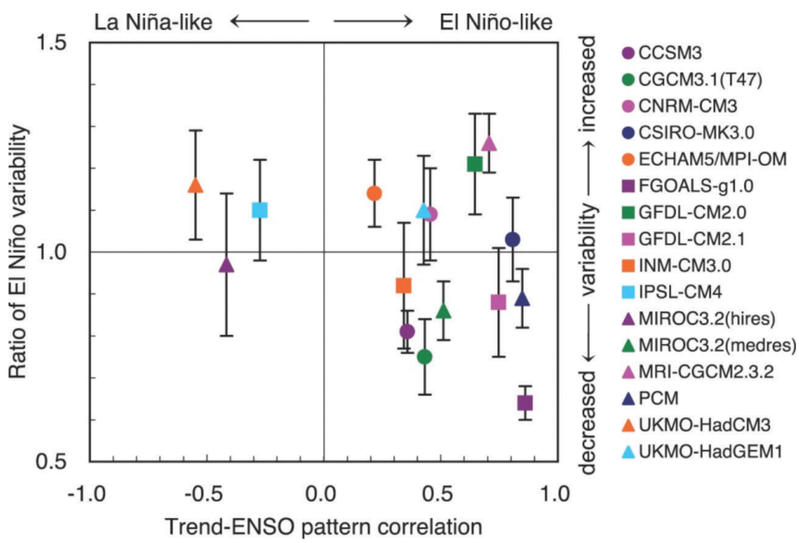


Figure B-4 Base state change in average tropical Pacific SSTs and change in El Niño variability simulated by AOGCMs. The base state change (horizontal axis) is denoted by the spatial anomaly pattern correlation coefficient between the linear trend of SST in the 1% yr–1 CO_2 increase climate change experiment and the first Empirical Orthogonal Function (EOF) of SST in the control experiment over the area 10°S to 10°N, 120°E to 80°W (reproduced from Yamaguchi and Noda, 2006). Positive correlation values indicate that the mean climate change has an El Niño–like pattern, and negative values are La Niña–like. The change in El Niño variability (vertical axis) is denoted by the ratio of the standard deviation of the first EOF of sea-level pressure (SLP) between the current climate and the last 50 years of the SRES A2 experiments (2051–2100), except for FGOALS-g1.0 and MIROC3.2(hires), for which the SRES A1B was used, and UKMO-HadGEM1, for which the 1% yr–1 CO_2 increase climate change experiment was used, in the region 30°S to 30°N, 30°E to 60°W with a five-month running mean (reproduced from van Oldenborgh et al., 2005). Error bars indicate the 95% confidence interval. Note that tropical Pacific base state climate changes with either El Niño–like or La Niña–like patterns are not permanent El Niño or La Niña events, and all still have ENSO interannual variability superimposed on that new average climate state in a future warmer climate. (From IPCC AR4 Secton 10.3.5.3, Figure 10.16; Meehl et al., 2007.)

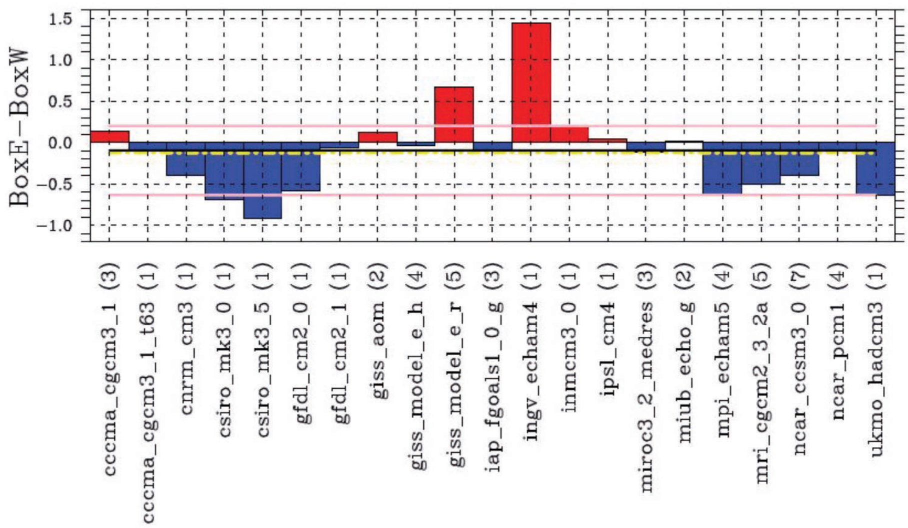


Figure B-5 The projected late 21st-century change in the difference in sea-level pressure between two boxes along the equator in the eastern and western Pacific in 21 CMIP3 models. The model identifiers are along the axis along with the number of realizations analyzed (in parentheses). (From Power & Kociuba, 2011.)

Two prominent gridded SST products from the UK Hadley Center (HadISST) (Rayner et al., 2003) and NOAA (ERSST) (Smith et al., 2008) actually indicate rather different trends over the 20th century in the tropical Pacific (Vecchi et al., 2008). Different atmospheric data sources also appear to provide somewhat contradictory results for 20th-century trends in the equatorial Pacific. Atmospheric re-analyses and some studies with atmospheric GCMs forced with observed SSTs suggest an intensification of the Walker circulation (Chen et al., 2008; Meng et al., 2011; Sohn & Park, 2010; Yu & Zwiers, 2010), while surface pressure and cloudiness reconstructions are consistent with a modest weakening of the Walker circulation (Deser et al., 2010a; Power & Kociuba, 2011). Recently, the situation has improved with the understanding that the atmospheric re-analysis projects are affected by a bias in observed surface winds over the ocean. Anemometer observations of winds from ships of opportunity make up an important input into the re-analyses. These anemometer "surface" wind measurements have been subject to a spurious trend to stronger values as the average size of ships in the world's fleet have increased. Recently, Tokinaga et al. (2011) have made a careful correction for this effect and, using their corrected data set for surface winds, have shown that the various observational data sets are indeed consistent with a slow weakening of the Walker circulation over the 20th century.

Of course, even trends over a century may reflect both the response to changed climate forcing and low-frequency natural unforced variations. Power and Kociuba (2011) make an attempt to separate these two effects in the observed basin-scale 20th-century changes in the tropical Pacific and conclude that 30% to 70% of the observed trend is the result of changing climate forcing through the century (which itself is mainly from increased GHG concentrations). This recently improved understanding of the 20th-century trends may contribute to more robust projections for 21st-century climate trends in the Pacific. As noted above, the CMIP3 models displayed considerable variation in their projected late 21st-century response to a given climate forcing scenario, even in terms of the changes in basin-scale features. If such models can be evaluated against our more robust picture of 20th-century climate evolution, then we may be able to produce a more consistent set of results for the Pacific. Certainly, this is one aspect where progress has been made since the AR4 report, and this new understanding will provide important context for the analysis of the CMIP5 model results. Irving et al. (2011) discuss some criteria for evaluating global climate models that may be used for climate projections in the Pacific region.

Regional projections from global coupled model results

Practical constraints in currently available computer resources have limited the resolution of global coupled ocean-atmosphere models that have been run for the extensive model intercomparison projects. For the CMIP3 models, the horizontal grid spacing of the models was typically ~200 km. For CMIP5, results from more models with grid spacing of ~100 km may be available, but this is still much too coarse to resolve explicitly the mountains on any of the Pacific Islands with significant orography, nor can the structure of mesoscale convective precipitation systems be adequately resolved. Despite these limitations, the coupled model projections might be expected to provide some information on the expected changes of temperature, wind, and rainfall in individual regions. The CMIP3 models have been analyzed extensively for the changes seen over the 21st century in runs forced with various emissions scenarios. Figure B-6 shows the change in DJF and JJA mean surface air temperature and precipitation between the late 21st century and the late 20th century in simulations forced by the SRESA1B emissions scenario (Meehl et al., 2007). The change here is determined by the multi-model ensemble of all the CMIP models. Stippling denotes regions where the mean change exceeds the intermodel standard deviation. Over the Pacific, the multi-model mean shows a robust pattern of warming that is larger near the equator and smaller in the sub-tropics. The multi-model mean change in precipitation shows increases along the equator and decreases over much of the sub-tropics. This basic pattern where "wet regions get wetter" under global warming has been explained as a result of increased moisture convergence due to higher absolute atmospheric humidity in the warmer climate (Held & Soden, 2006), although Xie et al. (2010) show the importance also of changing spatial gradients in the SST in modifying the rainfall over the oceans at tropical and subtropical latitudes. While the global warming–induced rainfall change seen in the multi-model mean is consistent with these general expectations, it is striking that over almost none of the tropical and subtropical Pacific in Figure B-6 does the magnitude of the mean change exceed the intermodel standard deviation.

The CMIP5 models results are now becoming available, and it will be interesting to see if the rainfall change projections for the tropical Pacific will be more robust in the newer models. Figure B-7 is a very preliminary first step in analyzing the CMIP5

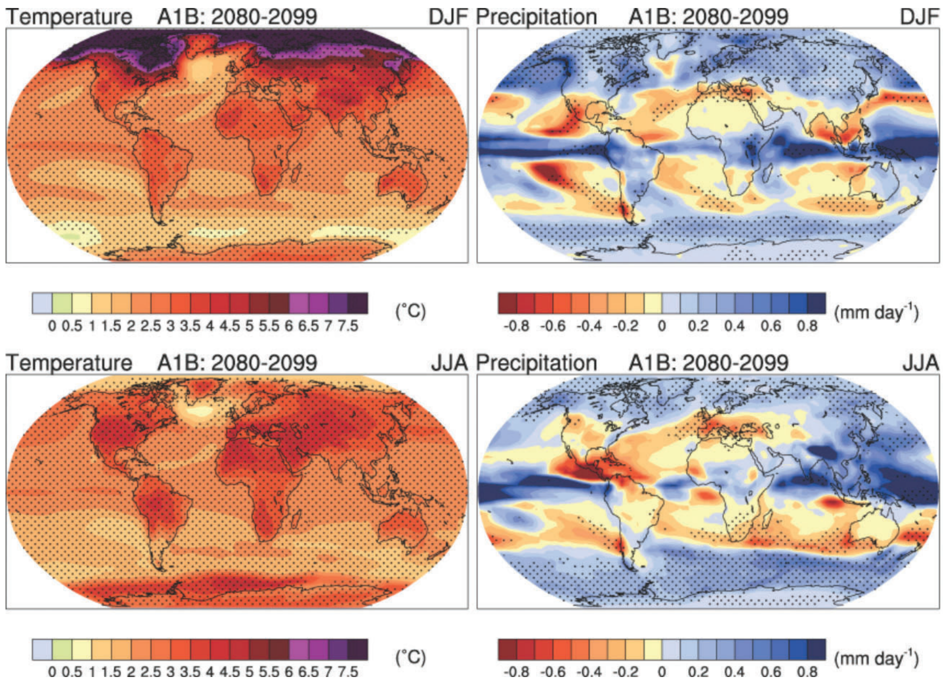


Figure B-6 The change over the 21st century in surface air temperature (left) and precipitation (right) in the multi-model ensemble of CMIP3 SRESA1B integrations. Results for December–February (top) and June–August (bottom). Stippling indicates where the magnitude of the multi-model mean change exceeds the inter-model standard deviation. From AR4. (From IPCC AR4 Secton 10.3.2.1, Figure 10.9; Meehl et al., 2007.)

models, in this case focusing on simulations with a single model (the Hadley Centre HADGEM2-ES). The results for 1985–2004 from four ensemble members for the "Historical" 20th-century run and from 2080–2099 from one "RCP4.5" 21st-century forced simulation are displayed. Shown are the results for the 20-year mean rainfall for each calendar month in each realization averaged over five individual boxes, corresponding roughly to the locations of the major groups of USAPI. The results from this one model suggest increased annual mean rainfall at all the USAPI locations, but the projected effects are modest except around Hawai'i , where the fall–early winter rainfall is projected to be very strongly enhanced (as much as a factor of two in some months) in the warmer climate.

High-resolution global atmospheric models

One approach that has been adopted to refine the coarse-resolution coupled model results has been integration of relatively fine-resolution global atmospheric models forced with the SST warming determined from coupled model projections. This potentially allows a more realistic simulation of the atmospheric responses, in particular in the mesoscales, which will have an impact on projected extreme events. Examples of such studies

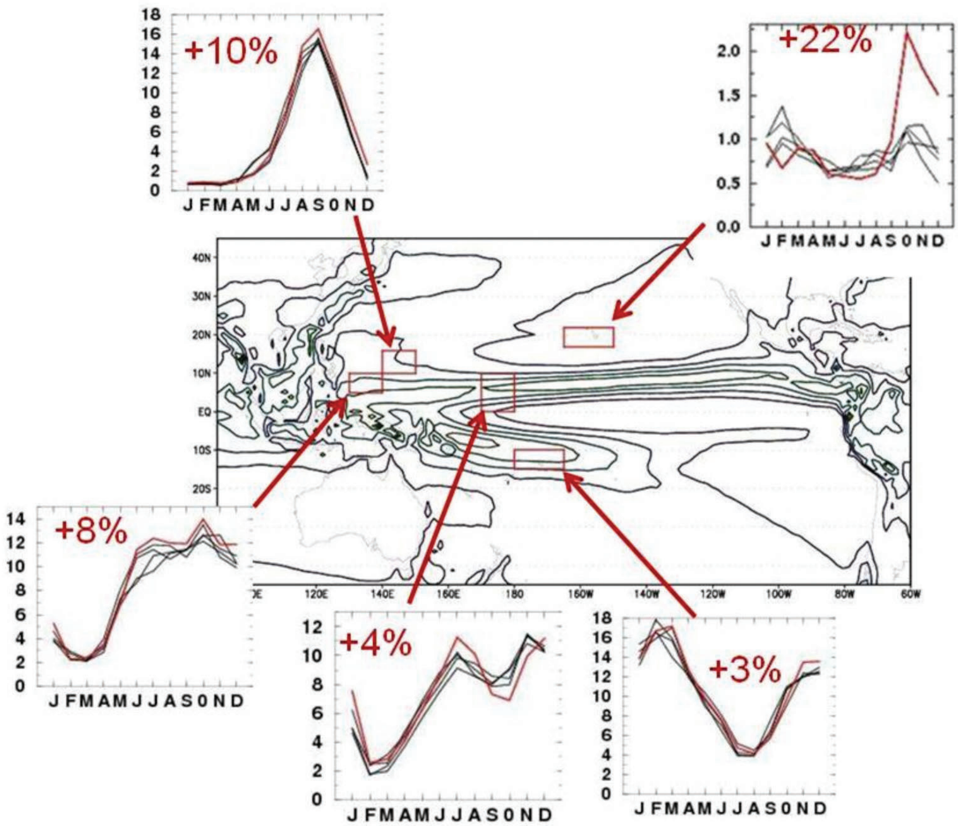


Figure B-7 CMIP5 climate change results from the Hadley Centre HADGEM2-ES model. Shown are the mean annual cycle of precipitation averaged over five individual boxes corresponding to the locations of the major groups of USAPI. Results for the late 20th century from the CMIP5 "Historical" simulation (black curves) and for the late 21st century from a RCP4.5 climate change projection simulation (red curves). Each curve represent results from 20 years of simulation. Results from four 20th-century ensemble members and from a single RCP4.5 realization. The red numbers indicate the percentage change of annual mean precipitation in the RCP4.5 results relative to the late 20th-century simulations. (Figure courtesy of Kevin Hamilton.)

include Kamiguchi et al. (2006), who used a ~20 km grid global atmospheric model to investigate global warming effects on precipitation extremes, and Li et al. (2010), who used a ~40 km global atmospheric model to project global warming effects on tropical cyclone climatology. For the Pacific Islands with significant mountains, such global models can begin to resolve some of the larger-scale topographic features and may simulate considerable amounts of orographic rainfall, but the global models still lack the resolution to adequately represent the local climates driven by topographic interactions with the atmospheric circulation. Such models may have some use in taking a first look at projected climate changes for individual islands and may be a useful self-consistent "test-bed" for evaluation of the statistical downscaling approaches that may be applied to producing high-resolution climate change projections.

Statistical downscaling of coarse-resolution model projections

Statistical downscaling aims to produce high-resolution projections of climate changes based on empirical relations between aspects of the large-scale circulation and local conditions. The empirical relations can be based on linear or nonlinear fits of large-scale predictors and local predicted fields, and the predictors can be based on raw data or data filtered to select dominant patterns. So far, this approach has not been widely applied in the insular Pacific, but there have been some recent studies focused on projecting aspects of Hawaiian rainfall (Elison Timm et al., 2011; Norton et al., 2011; Elison Timm & Diaz, 2009).

Regional model projections

An alternative approach to generating fine-resolution climate change projections uses our ability to explicitly simulate regional atmospheric circulation at small scales. Such projections may either embed a fine-resolution limited-area model within a much coarser resolution global model (Giorgi & Francisco, 2000) or use global atmospheric models with stretched grids that enable much finer resolution over some particular region (Fox-Rabinovitz et al., 2008; Lal et al., 2008). This approach has the advantage of being physically based and not needing assumptions about the relevance of present-day empirical relationships to future climate. The disadvantages include a typically heavy computational burden for such calculations and the inevitable inconsistency between the simulated flows on the coarse- and fine-resolution components of the grid.

This approach is being aggressively pursued now for climate projections for Hawaiʻi and will be applied to the other USAPI as well. The valleys and ridges, the broad and steep slopes, give the Hawaiian Islands a diversity of climates that are quite different from that over the surrounding oceans. The microclimates in the Hawaiian Islands range from humid and tropical windward flanks to dry leeward areas. Hawaiʻi represents a particular challenge for numerical modeling, and very fine resolution is necessary to resolve the fine-scale geographical variations. Some previous simulations of atmospheric flow over the Hawaiian Islands have used 1.5 to 3 km horizontal grid spacings as small as 1.5 km, but these have been for short-term (a few days or less) simulations (Zhang et al., 2005a, 2005b) or, at most, for seasonal forecasts (Van Nguyen et al., 2010). Zhang et al. (2005b) showed great improvement in simulations for Hawaiʻi in a regional model when horizontal resolution was enhanced from 10 km to 1.5 km.

A current project at IPRC is applying the Advanced Research Weather Research and Forecasting (WRF-ARW) model to climate simulation in Hawaiʻi and will soon provide high-resolution regional model climate projections using boundary conditions taken from CMIP3 and CMIP5 global simulations. The simulation of the trade wind boundary layer regime has been a particular challenge for numerical models (Wyant et al., 2010; Zhang et al., 2011), but the recent success reported by Zhang et al. (2011) in this regard using a modified version of the WRF-ARW model underpins the current effort at very fine resolution Hawaiʻi climate simulation (Zhang et al., 2012). Preliminary results for the rainfall over the islands in a simulation of the year 2006 driven by observed SSTs and lateral boundary conditions are shown in Figure B-8. This simulation used a nested grid with a 3 km horizontal resolution in the inner grid covering the main Hawaiian Islands and adjacent ocean areas.

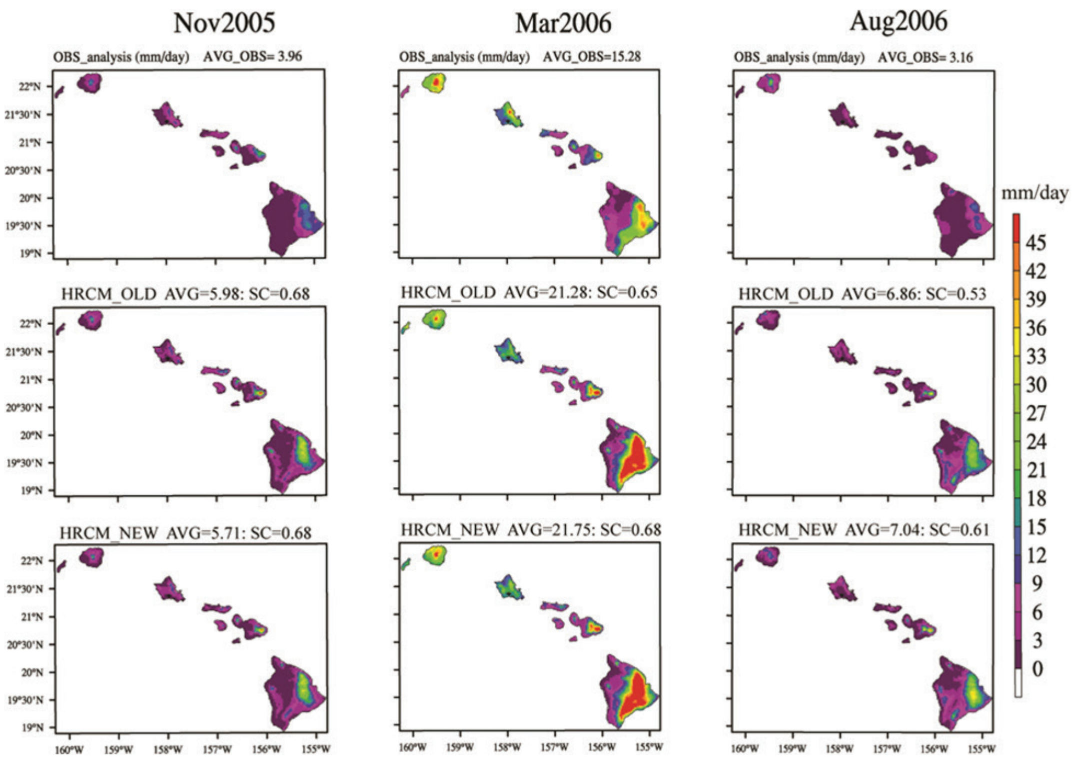


Figure B-8 Monthly rainfall over the main Hawaiian Islands from a one-year simulation with the regional WRF-ARW model modified as described in Zhang et al. (2012). Results from two versions of the model are shown in the middle and lower rows. Observations in the top row are objective analyses based on rain-gauge observations at a large number of stations. Results for November 2005, March 2006, and August 2006 are shown.

Appendix C

Members of the Pacific Assessment Core Science Team

Stephen Anthony
Director, USGS Pacific Islands Water Science Center
santhony@usgs.gov

Tim Brown
Director, Western Regional Climate Center
Tim.Brown@dri.edu

Jeff Burgett
Science Manager, Pacific Islands Climate Change Cooperative
jeff_burgett@fws.gov

Dolan Eversole
Pacific Region Coordinator, Coastal Storms Program
eversole@hawaii.edu

Melissa Finucane
Senior Fellow, East-West Center; Lead Principal Investigator, Pacific RISA
FinucanM@eastwestcenter.org

Charles Fletcher
Associate Dean, SOEST, University of Hawai'i at Mānoa
fletcher@soest.hawaii.edu

Kevin Hamilton
Director, International Pacific Research Center; Professor of Meteorology, University of Hawaiʻi
kph@hawaii.edu

Victoria W. Keener
Fellow, East-West Center; Program Manager, Pacific RISA
KeenerV@eastwestcenter.org

Dawn Kotowicz
Social Research Project Manager, NOAA Pacific Islands Fisheries Science Center
dawn.kotowicz@noaa.gov

John J. Marra
Regional Climate Services Director, Pacific Region; Adjunct Fellow, East-West Center
john.marra@noaa.gov

Mark Merrifield
Associate Professor, Department of Oceanography, SOEST, University of Hawai'i at Mānoa
markm@soest.hawaii.edu

Stephen E. Miller
Science Advisor, US Fish and Wildlife Service
stephen_e_miller@fws.gov

Britt Parker
Climate Coordinator; NOAA Coral Reef Conservation Program
britt.parker@noaa.gov

Noriko Shoji
Physical Scientist, NOAA
noriko.shoji@noaa.gov

Deanna Spooner
Coordinator, Pacific Islands Climate Change Cooperative
deanna.spooner@piccc.net

Adam Stein
Geospatial Technician, NOAA Pacific Services Center
adam.stein@noaa.gov

William V. Sweet
Oceanographer, NOAA Center for Operational Oceanographic Products and Services
William.Sweet@noaa.gov

Jean Tanimoto
Coastal Program Coordinator, NOAA Pacific Services Center
jean.tanimoto@noaa.gov

Appendix D

Members of the Pacific Assessment Steering Committee

Tim Brown
Director, Western Regional Climate Center
Tim.Brown@dri.edu

Jeff Burgett
Science Manager, Pacific Islands Climate Change Cooperative
jeff_burgett@fws.gov

Dolan Eversole
Pacific Region Coordinator, Coastal Storms Program
eversole@hawaii.edu

Melissa L. Finucane
Senior Fellow, East-West Center; Lead Principal Investigator, Pacific RISA
FinucanM@eastwestcenter.org

Charles Fletcher
Associate Dean, SOEST, University of Hawaiʻi at Mānoa
fletcher@soest.hawaii.edu

Victoria W. Keener
Fellow, East-West Center; Program Manager, Pacific RISA
KeenerV@eastwestcenter.org

Dawn Kotowicz
Social Research Project Manager, NOAA Pacific Islands Fisheries Science Center
dawn.kotowicz@noaa.gov

John J. Marra
Regional Climate Services Director, Pacific Region; Adjunct Fellow, East-West Center
john.marra@noaa.gov

Stephen E. Miller
Science Advisor, US Fish and Wildlife Service
stephen_e_miller@fws.gov

Noriko Shoji
Physical Scientist, NOAA
noriko.shoji@noaa.gov

Deanna Spooner
Coordinator, Pacific Islands Climate Change Cooperative
deanna.spooner@piccc.net

Adam Stein
Geospatial Technician, NOAA Pacific Services Center
adam.stein@noaa.gov

Jean Tanimoto
Coastal Program Coordinator, NOAA Pacific Services Center
jean.tanimoto@noaa.gov

Appendix E

PIRCA Water and Drought Technical Workshop, November 17, 2011

On November 17, 2011, the Pacific Regional Integrated Sciences and Assessments (RISA) program convened a one-day workshop on past and future trends in climate, freshwater resources, and drought in support of regional efforts for the National Climate Assessment (NCA), at the East-West Center in Honolulu, Hawaiʻi. The Pacific Islands Regional Climate Assessment (PIRCA) brought together scientific experts in climatology and hydrology from around the Pacific Islands region to build consensus around relevant observed and future trends in the Central North Pacific, Western North Pacific, and Central South Pacific sub-regions.

Co-Chairs

Steve Anthony, Director of the USGS Pacific Islands Water Science Center

Dr. Victoria Keener, Research Fellow at the East-West Center, Program Manager of the Pacific RISA

Facilitator

Dr. Jonathan Likeke Scheuer, Consultant (scheuerj001@hawaii.rr.com)

Key Outcomes

- Throughout the course of the day, participants came to a discussion-based consensus on "Iconic Figures" to be highlighted in the "Water and Drought" chapter of the report, as well on historic trends in air temperature, precipitation, extreme precipitation, and streamflow on a sub-regional level.
- Through a presentation on current knowledge of regional climate projections, participants identified regionally relevant research that they had confidence in presenting in the chapter.
- Experts came to consensus on key regional findings and themes to emphasize in the climate and hydrology nexus.
- Participants identified expected impacts of climate variability and change on freshwater resources sub-regionally.

Participants

Hanna Annamalai
Senior Researcher, International Pacific Research Center (IPRC), University of Hawai'i at Mānoa
hanna@hawaii.edu

Ryan Bailey
Researcher, University of Guam
rtbailey@engr.colostate.edu

Tim Brown
Director, Western Regional Climate Center (WRRC); Research Professor, Division of Atmospheric Sciences; Desert Research Institute (DRI) Reno
Tim.Brown@dri.edu

Jeff Burgett
Science Manager, Pacific Islands Climate Change Cooperative (PICCC)
jeff.burgett@piccc.net

Pao-Shin Chu
Professor and State Climatologist, School of Ocean and Earth Science and Technology (SOEST), University of Hawai'i at Mānoa
chu@hawaii.edu

Kati Corlew
Project Assistant, Pacific RISA
corlewk@eastwestcenter.org

Paula Cutillo
Hydrogeologist, Water Resources Division, National Park Service
Paula_Cutillo@nps.gov

Henry Diaz
Research Climatologist, NOAA, Earth System Research Laboratory
henry.f.diaz@noaa.gov

Aly El-Kadi
Professor, Associate Researcher and Assistant Director, Water Resources Research Center (WRRC), University of Hawai'i at Mānoa
elkadi@hawaii.edu

Melissa Finucane
Senior Research Fellow, East-West Center
FinucanM@eastwestcenter.org

Charles (Chip) Fletcher
Professor, School of Ocean and Earth Science and Technology (SOEST), University of Hawai'i at Mānoa
fletcher@soest.hawaii.edu

Tom Giambelluca
Professor, Deptartment of Geography, University of Hawai'i at Mānoa
thomas@hawaii.edu

Kevin Hamilton
Director International Pacific Research Center (IPRC), University of Hawai'i at Mānoa
kph@hawaii.edu

Scot Izuka
Hydrologist, USGS Pacific Water Science Center
skizuka@usgs.gov

John Jenson
Professor of Environmental Geology, Water and Environmental Research Institute (WERI), University of Guam
jjenson@uguam.uog.edu

Victoria Keener
Research Fellow, East-West Center
KeenerV@eastwestcenter.org

Kevin Kodama
Senior Service Hydrologist, Honolulu Weather Forecast Office, Hawai'i
kevin.kodama@noaa.gov

Mike Kruk
Senior Scientific Expert, STG Inc.; National Climatic Data Center (NCDC)
michael.kruk@noaa.gov

Mark Lander
Professor of Water Resources Engineering, Water and Environmental Research Institute (WERI), University of Guam
mlander@uguam.uog.edu

Chester Lao
Hydologist-Geologist (retired, 43 years), Honolulu Board of Water Supply
ch2lao@yahoo.com

Nancy Lewis
Director, Research Program, East-West Center
LewisN@EastWestCenter.org

Alan Mair
Post-Doctoral Fellow, Water Resources Research Center (WRRC), University of Hawai'i at Mānoa
mair@hawaii.edu

John J. Marra
Director, Pacific Regional Climate Service, NOAA
john.marra@noaa.gov

Lisa Miller
Hydrologist, USGS Rocky Mountain Area
ldmiller@usgs.gov

Rachel Miller
Project Assistant, Pacific RISA
millerr@eastwestcenter.org

Delwyn Oki
Hydrologist, USGS Pacific Water Science Center
dsoki@usgs.gov

Jonathan Scheuer
Meeting Facilitator
scheuerj001@hawaii.rr.com

Margaret Smith
PIRCA Report Integrator, East-West Center
margaretsmith@gmail.com

Mark Stege
RMI Team Leader, Asian Development Bank (ADB) Climate Change Adaptation Preparation Project
markhstege@gmail.com

Sharla Stevenson
National Park Service, PhD Candidate, Department of GeoSciences, Colorado State University
Sharla_Stevenson@nps.gov

Billy Sweet
Oceanographer, NOAA Center for Operational Oceanographic Products and Services
William.Sweet@noaa.gov

Oliver Elison Timm
Assistant Researcher, International Pacific Research Center (IPRC), University of Hawai'i at Mānoa
timm@hawaii.edu

Appendix F

PIRCA Sea-Level Rise and Coastal Inundation Extremes: Methodologies, Indicators, Impacts, and Visualization Workshop, January 10–12, 2012

On January 10 and 11, 2012, at the East-West Center in Honolulu, Hawai‘i, NOAA brought together government, academic, and other experts to share knowledge and explore our current understanding of sea-level rise and coastal inundation in the Pacific Islands. Funded through the NOS Coastal Storms Program, with support from SeaGrant, University of Hawaii at Manoa; NOAA Center for Operational Oceanographic Products & Services (COOPS); NOAA Coastal Services Center (CSC), Pacific Services Center (PSC) and PRiMO; and NOAA National Climate Data Center (NCDC) and PaCIS.

Key Objectives

- To solicit input from experts leading to consensus on regional best practices and a consistent methodology for the formulation of probabilistic sea-level rise (SLR)/coastal inundation extremes scenarios in the Pacific Islands, and explore how such practices might be advanced
- To evaluate the state of knowledge on SLR/costal inundation knowledge and impacts within sub-regions of the Pacific, including the identification of data needs and gaps
- To solicit technical input on visualization tools that can be used to support scenario planning

Organizing Committee

Dolan Eversole, SeaGrant, University of Hawai'i at Mānoa

Doug Marcy, NOAA CSC

John J. Marra, NOAA NCDC

William Sweet, NOAA COOPS

Adam Stein, NOAA PSC

Facilitators:

Arlene O'Donnell, Eastern Research Group, Inc.

Martina McPherson, Eastern Research Group, Inc

Key Outcomes:

- Consensus on elements that need to be incorporated into regional best practices and methodologies for the formulation of probabilistic SLR/coastal inundation extremes scenarios in the Pacific Islands, and recommendations on how such practices might be advanced
- Assessment of SLR/coastal inundation knowledge and impacts by sub-region/island
- Recommendations concerning key scientific and technical issues as they pertain to the application of the results of SLR/coastal inundation analysis in visualization tools

Participants

Amanda Amjadali
Ocean Climate Manager, Australian Bureau of Meteorology
a.amjadali@bom.gov.au

Don Chambers
Associate Professor, University of South Florida
dchambers@marine.usf.edu

Jérome Aucan
Researcher (IRD), Institute for Research and Development (IRD, France)
jerome.aucan@ird.fr

Rashed Chowdhury
Principal Research Scientist, University of Hawaiʻi /Pacific ENSO Applications Climate Center, Joint Institute for Marine and Atmospheric Research
rashed@hawaii.edu

Matthew Barbee (Observer)
CCG Cartographer/Supervisor, University of Hawaiʻi, School of Ocean and Earth Science and Technology
mbarbee@hawaii.edu

Frank Colberg
Research Scientist, Commonwealth Scientific and Industrial Research Organisation, Marine and Atmospheric Research
Frank.Colberg@csiro.au

Patrick Caldwell
Liaison, National Oceanic and Atmospheric Administration, National Oceanographic Data Center
patrick.caldwell@noaa.gov

Hannah Cooper (Observer)
Researcher, University of Hawaiʻi at Mānoa Coastal Geology Group
hannahco@hawaii.edu

Edward Carlson
Pacific Region Geodetic Advisor, National Oceanic and Atmospheric Administration, National Ocean Service/ National Geodetic Survey
ed.carlson@noaa.gov

Stanton Enomoto (Observer)
Cultural Adaptation Coordinator, Pacific Islands Climate Change Cooperative
Stanton.Enomoto@piccc.net

Dolan Eversole
NOAA Coastal Storms Program Regional Coordinator, University of Hawaiʻi Sea Grant
eversole@hawaii.edu

Doug Harper (Note Taker)
Coastal Planner
National Oceanic and Atmospheric Administration, National Ocean Service/Pacific Services Center
Douglas.Harper@noaa.gov

Charles (Chip) Fletcher
Associate Dean for Academic Affairs/Professor, University of Hawaiʻi, School of Ocean and Earth Science and Technology
fletcher@soest.hawaii.edu

John Hunter
Sea-level Oceanographer, Antarctic Climate & Ecosystems Cooperative Research Centre
john.hunter@utas.edu.au

Roland Fuchs (Observer)
East-West Center, Senior Fellow
fuchsr@eastwestcenter.org

David Jay
Professor, Portland State University Department of Civil and Environmental Engineering
djay@cecs.pdx.edu

Ayesha Genz
Research Associate, University of Hawaiʻi Sea Level Center
agenz@hawaii.edu

Haunani Kane (Observer)
University of Hawaii at Mānoa Coastal Geology Group
hkane@hawaii.edu

John Hall
Program Manager for Resource Conservation and Climate Change, Department of Defense, Strategic Environmental Research and Development Program/Environmental Security Technology Certification Program
john.hall@osd.mil

Victoria Keener (Observer)
Research Fellow/Program Manager, East-West Center, Pacific Regional Integrated Science and Assessment
KeenerV@eastwestcenter.org

Laura Hamilton (Note Taker)
NOAA Pacific Region Coordinator, National Oceanic and Atmospheric Administration; National Environmental Satellite, Data, and Information Service
laura.hamilton@noaa.gov

Jens Kruger
Team Leader (Oceanography), Secretariat of the Pacific Regional Environment Programme
jkruger@sopac.org

Mark Lander
Meterologist, Water and Environmental Institute of the Western Pacific, UOG Station
mlander@uguam.uog.edu

Mark Merrifield
Director, University of Hawaiʻi Sea Level Center
markm@soest.hawaii.edu

Penny Larin
Program Analyst, National Oceanic and Atmospheric Administration, Coastal Services Center, NOAA Pacific Services Center
penny.larin@noaa.gov

Marnie Meyer (Observer)
Planning and Policy Analyst, State of Hawai'i , Office of Planning, Hawai'i Coastal Zone Management Program
mmeyer@dbedt.hawaii.gov

Douglas Marcy
Coastal Hazards Specialist, National Oceanic and Atmospheric Administration, National Ocean Service Coastal Services Center
doug.marcy@noaa.gov

Gary Mitchum
Associate Dean/Professor, University of South Florida – College of Marine Science
mitchum@marine.usf.edu

John J. Marra
Pacific Regional Climate Services Director, National Oceanic and Atmospheric Administration, Regional Climate Services
john.marra@noaa.gov

Steve Nerem
Professor, University of Colorado
nerem@colorado.edu

Martina McPherson
Environmental Scientist, Eastern Research Group, Inc.
Martina.McPherson@erg.com

Arleen O'Donnell
Vice President, Eastern Research Group, Inc.
arleen.odonnell@erg.com

Melisa Menendez
Research Scientist, UC-IHCantabria
menendezm@unican.es

Doug Ramsay
Manager, Pacific Rim, National Institute of Water & Atmospheric Research, Ltd
Doug.Ramsay@niwa.co.nz

Peter Ruggiero
Associate Professor, Oregon State University
ruggierp@science.oregonstate.edu

Claudia Tebaldi
Research Scientist, Climate Central
ctebaldi@climatecentral.org

Giovanni Sella
CORS Program Manager, National Oceanic and Atmospheric Administration, National Geodetic Survey
Giovanni.Sella@noaa.gov

Keith Thompson
Professor, Dalhousie University, Department of Oceanography
keith.thompson@dal.ca

Margaret Smith (Observer)
East-West Center, Pacific Islands Regional Climate Assessment
margaretsmith@gmail.com

Phil Thompson (Observer)
Assistant Researcher, University of Hawai'i, Joint Institute for Marine and Atmospheric Research (JIMAR)

Thomas Smith
Hydraulic Engineer, United States Army Corps of Engineers
Thomas.D.Smith@usace.army.mil

Stacey Tighe (Observer)
Coastal and Marine Science & Policy Specialist, Independent Consultant
Stacey.tighe@gmail.com

Curt Storlazzi
Research Oceanographer, United States Geological Survey – Pacific Coastal and Marine Science Center
cstorlazzi@usgs.gov

Bill Ward (Observer)
Environmental Scientific and Services Division Chief, National Oceanic and Atmospheric Administration, National Weather Service/Pacific Region
bill.ward@noaa.gov

William Sweet
Oceanographer, National Oceanic and Atmospheric Administration, Center for Operational Oceanographic Products and Services
William.Sweet@noaa.gov

Appendix G

PIRCA Ecosystems Technical Workshop, January 18–19, 2012

On January 18-19, 2012, the Pacific Islands Climate Change Cooperative (PICCC) and the Pacific Regional Integrated Sciences and Assessments (RISA) program convened a two-day workshop on past and future trends in climate, and impacts to marine, freshwater, and terrestrial ecosystems in support of regional efforts for the National Climate Assessment (NCA), at the East-West Center in Honolulu, Hawai'i. The Pacific Islands Regional Climate Assessment (PIRCA) brought together scientific experts in climatology and ecological impacts from around the Pacific Islands region to build consensus around relevant observed and future trends in the Central North Pacific, Western North Pacific, and Central South Pacific sub-regions.

Co-Chairs

Britt Parker, Climate Coordinator, NOAA Coral Reef Conservation Program

Dr. Stephen E. Miller, Science Advisor and Assistant Field Supervisor for Climate Change and Strategic Habitat Conservation, US Fish and Wildlife Service Pacific Islands Office

Facilitator

Dr. Jonathan Likeke Scheuer, Consultant (scheuerj001@hawaii.rr.com)

Key Outcomes

- Through presentations on current knowledge of regional historical climatologies and climate projections, participants identified regionally relevant research that they had confidence in presenting in the chapter.
- Participants identified key climate variables of concern and key marine, freshwater, and terrestrial ecosystems of concern.
- Participants identified expected impacts of climate variability and change on marine, freshwater, and terrestrial ecosystems regionally and sub-regionally.
- Participants discussed priorities over the next decade for managers of marine, freshwater, and terrestrial ecosystems based on the impacts of climate variability and change and other stressors.
- Participants identified cross-ecosystem impacts and synergetic impacts of climate and non-climate stressors to key ecosystems.

Participants

Fred Amidon
US Fish and Wildlife Service, Pacific Islands Office

Russell Brainard
Supervisory Oceanographer/Division Chief, Coral Reef Ecosystem Division, NOAA NMFS-Pacific Islands Fisheries Science Center
Rusty.Brainard@noaa.gov

Jeff Burgett
Science Manager, Pacific Islands Climate Change Cooperative
jeff.burgett@piccc.net

Susan Cordell
Research Ecologist, USDA US Forest Service
Scordell01@fs.fed.us

David Duffy
Unit Leader, Pacific Cooperative Studies Unit, University of Hawaiʻi
dduffy@hawaii.edu

Stanton Enomoto
Cultural Adaptation Coordinator, Pacific Islands Climate Change Cooperative
Stanton.Enomoto@piccc.net

Douglas Fenner
Coral Reef Monitoring Ecologist, American Sāmoa Department of Marine and Wildlife Resources
douglasfenner@yahoo.com

Melissa Finucane
Senior Research Fellow, East-West Center
FinucanM@eastwestcenter.org

Lucas Fortini
Research Ecologist, Pacific Islands Climate Change Cooperative
Lucas.fortini@piccc.net

Tom Giambelluca
Professor, Department of Geography, University of Hawai'i at Mānoa
thomas@hawaii.edu

Christian Giardina
Research Ecologist, Pacific Southwest Research Station, USDA US Forestry Service
cgiardina@fs.fed.us

Kevin Hamilton
Director, International Pacific Research Center (IPRC), University of Hawai'i at Mānoa
kph@hawaii.edu

Don Hess
Vice President of Academic and Student Affairs, College of the Marshall Islands
cmihess@gmail.com

Jim Jacobi
Biologist, US Geological Survey
jjacobi@usgs.gov

Victoria Keener
Research Fellow, East-West Center
KeenerV@eastwestcenter.com

Jean Kenyon
Inventory and Monitoring Specialist, Hawaiian & Pacific Islands National Wildlife Refuge Complex, US Fish and Wildlife Service
Jean_kenyon@fws.gov

Eric Kingma
Enforcement/NEPA Coordinator, Western Pacific Regional Fishery Management Council
eric.kingma@noaa.gov

Greb Koob
State Biologist, USDA NRCS
Gregory.koob@hi.usda.gov

Richard McKenzie
Research Ecologist, Institute of Pacific Islands Forestry, USDA Forest Service
rmackenzie@fs.fed.us

Patricia Manley
Program Manager, Pacific Southwest Research Station, USDA Forest Service
Pmanley@fs.fed.us

John J. Marra
Director, Pacific Regional Climate Service, NOAA
john.marra@noaa.gov

Stephen E. Miller
Science Advisor and Assistant Field Supervisor for Climate Change and Strategic Habitation Conservation, US Fish and Wildlife Service Pacific Islands Office
Stephen_E_Miller@fws.gov

Britt Parker
Climate Coordinator, NOAA Coral Reef Conservation Program
Britt.parker@noaa.gov

Dan Polhemus
Coastal Conservation Program Manager Pacific Islands Fish and Wildlife Office, US Fish and Wildlife Service
Dan_polhemus@fws.gov

Jeff Polovina
Chief, Ecosystems & Oceanography Division, NOAA Pacific Islands Fisheries Science Center
Jeffrey.polovina@noaa.gov

Bob Richmond
Researcher, University of Hawai'I, Kewalo Marine Lab
richmond@hawaii.edu

Haldre Rogers
Biologist, University of Washington
haldre@uw.edu

Jonathan Scheuer
Meeting Facilitator
scheuerj001@hawaii.rr.com

Heidi Schuttenberg
Karsten Shein, Applied Climatologist, NOAA National Climatic Data Center
Karsten.Shein@noaa.gov

Nori Shoji
Science Operations Lead, NOAA NMFS Pacific Islands Fisheries Science Center
Noriko.Shoji@noaa.gov

Rebecca Skeele
Coral Reef Regional Management Support Staff, CNMI Coastal Resource Management Office
Rebecca.skeele@crm.gov.mp

Margaret Smith
PIRCA Report Integrator, East-West Center
margaretsmith@gmail.com

Deanna Spooner
Coordinator, Pacific Islands Climate Change Cooperative
deanna.spooner@piccc.net

Deborah Swanson
Recorder
stoneswanson@hawaii.rr.com

Billy Sweet
Oceanographer, NOAA Center for Operational Oceanographic Products and Services
William.Sweet@noaa.gov

Jared Underwood
US Fish and Wildlife Service-Refuges
Jared.underwood@fws.gov

Adam Vorsino
Pacific Islands Fish and Wildlife Office, US Fish and Wildlife Service
Adam.vorsuno@fws.gov

Appendix H

Summary of Workshop Evaluations

Water and Drought Workshop

A total of 34 people participated in the water and drought workshop, held November 17, 2011. Participants included 11 people from the East-West Center and Pacific RISA and its affiliates and 23 from other organizations. Of the 23 participants from outside organizations, 20 (87%) were male. Fifty-two percent of participants were associated with the University of Hawai'i, University of Guam, or Colorado State University. Thirteen percent represented NOAA, 13% represented USGS, 9% represented other Federal agencies, and 13% represented other non-profit, public, or international agencies. Twenty-six percent of the participants were hydrologists or hydrologist-geologists, 22% were university professors, 34% were other scientists and researchers, and 17% were other professions. We received 17 completed evaluation questionnaires.

Sea-level Rise and Coastal Inundation Workshop

A total of 30 people participated in the sea-level and coastal inundation workshop, held January 10–11, 2012. Twenty three participants (77%) were male. Forty-three percent of participants were associated with either a US or international university. Of the remaining participants, 17% represented NOAA, 10% represented other Federal agencies, 10% represented private US-based organizations, 10% represented international governmental institutions, and 10% represented other international organizations. Twenty-three percent of the participants were university professors, 23% were managers or directors, 40% were scientists and researchers, and 13% represented other professions. We received 18 completed evaluation questionnaires.

Ecosystems Workshop

A total of 27 people participated in the ecosystems workshop, held January 18–19, 2012. Twenty participants (74%) were male. Fifteen percent of participants represented NOAA, 15% represented USFS, 19% represented USFWS, 15% represented other federal agencies, 19% represented colleges or universities, 7% represented international government agencies, and 11% represented other organizations or their organizational affiliation was unknown. Twenty-two percent of the participants were university professors or other university affiliates, 19% were ecologists, 15% were biologists, 15% were other scientists or researchers, 19% were managers or administrators, and 11% represented other professions or were unknown. We received 15 completed evaluation questionnaires.

Workshop Evaluations

Across all three workshops, respondents were very positive in their evaluations (Table H-1). A large majority of respondents rated the workshops as useful, reported that their comments and ideas were captured well, and thought that this was a good start to developing a sustained process for assessing the impacts of climate change. Participants were satisfied with decisions about which climate variables were discussed and the process of coming to scientific consensus via the workshop. A large majority of participants indicated they would be willing to participate in a consensus workshop again in the future.

Table H-1: Summary of responses to evaluation questionnaire at each workshop

	Water and Drought Workshop (percent of respondents)	Sea-level Rise and Coastal Inundation Workshop (percent of respondents)	Ecosystems Workshop (percent of respondents)
Overall evaluation of "moderately" or "extremely" useful	100.0	94.4	100.0
Comments and ideas were captured "extremely well" or "well"	94.1	83.3	86.7
A "good" or "very good" start to developing a sustained process for assessing the impacts of climate change	94.1	94.5	100.0
"Moderately" or "extremely" satisfied with the final decision about which essential climate variables were discussed	88.2	N/A	93.3
"Moderately" or "extremely" satisfied with the process of coming to scientific consensus via the workshop	94.1	94.4	86.6
Willing to participate in an activity like this consensus workshop again	100.0	88.9	93.3

References

Adger, W. N., Agrawala, S., Mirza, M. M. Q., Conde, C., O'Brien, K., Pulhin, J., Pulwarty, R., et al. (2007). Assessment of adaptation practices, options, constraints and capacity. In M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden, & C. E. Hanson (Eds.), *Climate change 2007: Impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 717–743). Cambridge, UK, and New York, NY: Cambridge University Press.

Allan, J. C., & Komar, P. D. (2006). Climate controls on US West Coast erosion processes. *Journal of Coastal Research*, *223*, 511–529. doi:10.2112/03-0108.1

Anderson, C. L. (2012a). *Overview of climate risk reduction in the US Pacific Islands Freely Associated States* (Technical Report No. 201103B). Honolulu, HI: Hazards, Climate & Environment Program, University of Hawai'i Social Science Research Institute.

Anderson, C. L. (2012b). *Overview of climate risk reduction in the US Pacific Islands hazard mitigation planning efforts* (Technical Report No. 201103A). Honolulu, HI: Hazards, Climate & Environment Program, University of Hawai'i Social Science Research Institute.

Anderson, C. L. (2012c). *Analysis of integrating disaster risk reduction and climate change adaptation in the US Pacific Islands and Freely Associated States* (Technical Report No. 201105). Honolulu, HI: Hazards, Climate & Environment Program, University of Hawai'i Social Science Research Institute.

Annamalai, H., Sooraj, K. P., Kumar, A., & Wang, H. (2011). Feasibility of dynamical seasonal precipitation prediction for the Pacific Islands. *Science and Technology Infusion Climate Bulletin* (pp. 192–203). Presented at the 36th NOAA Annual Climate Diagnostics and Prediction Workshop, 2011 October 3-6, Fort Worth, TX. Retrieved from http://www.weather.gov/ost/climate/STIP/36CDPW/36cdpw-hanna.pdf

Arata, J. A., Sievert, P. R., & Naughton, M. B. (2009). *Status assessment of Laysan and Black-footed Albatrosses, North Pacific Ocean, 1923-2005* (US Geological Survey Scientific Investigations Report No. 2009-5131). Retrieved from http://pubs.usgs.gov/sir/2009/5131/

Ashok, K., & Yamagata, T. (2009). Climate change: The El Niño with a difference. *Nature*, *461*(7263), 481–484. doi:10.1038/461481a

Atkinson, C. T., & LaPointe, D. A. (2009a). Ecology and pathogenicity of avian malaria and pox. In M. T. K. Pratt, M. C. T. Atkinson, M. P. C. Banko, M. J. D. Jacobi, & M. B. L. Woodworth (Eds.), *Conservation biology of Hawaiian forest birds: Implications for island avifauna* (pp. 234–252). New Haven, CT: Yale University Press.

Atkinson, C. T., & LaPointe, D. A. (2009b). Introduced avian diseases, climate change, and the future of Hawaiian honeycreepers. *Journal of Avian Medicine and Surgery*, *23*(1), 53–63. doi:10.1647/2008-059.1

Atkinson, C. T., & Utzurrum, R. B. (2010). *Changes in prevalence of avian malaria on the Alakai'i Plateau, Kaua'i. Hawai'i, 1997-2007* (Hawaii Cooperative Studies Unit Technical Report No. HCSU-017). University of Hawaii at Hilo. Retrieved from http://hilo.hawaii.edu/hcsu/documents/TRHCSU017AtkinsonChangesinPrevalenceofAvianMalariaFINAL.pdf

Aucan, J., Hoeke, R., & Merrifield, M. A. (2012) Wave-driven sea level anomalies at the Midway tide gauge as an indicator of North Pacific storminess over the past 60 years. *Geophysical Research Letters*, 39, L17603. doi:10.1029/2012GL052993

Austin, J., Overbeek, J. W., Larcombe, J., & Alejandrino-Yap, M. C. (2011). *Pacific Islands performance indicators*. Sydney, Australia: Pacific Region Infrastructure Facility. Retrieved from http://www.theprif.org/sites/theprif.org/files/PIPIs%20Report.pdf

Australian Bureau of Meteorology & CSIRO. (2011). *Climate change in the Pacific: Scientific assessment and new research. Volume 1: Regional overview. Volume 2: Country reports.* Retrieved from http://www.cawcr.gov.au/projects/PCCSP/

Bailey, R. T., Jenson, J. W., & Olsen, A. E. (2010). Estimating the ground water resources of atoll islands. *Water*, *2*(1), 1–27. doi:10.3390/w2010001

Bailey, R. T., & Jenson, J. W. (2011). *Groundwater resources analysis of atoll islands in the Federated States of Micronesia using an algebraic model* (Technical Report No. 134). University of Guam, Water and Environmental Research Institute of the Western Pacific. Retrieved from http://www.weriguam.org/reports/item/groundwater-resources-analysis-of-atoll-islands-in-the-federated-states-of-micronesia-using-an-algebraic-model

Ballu, V., Bouin, M.-N., Siméoni, P., Crawford, W. C., Calmant, S., Boré, J.-M., Kanas, T., et al. (2011). Comparing the role of absolute sea-level rise and vertical tectonic motions in coastal flooding, Torres Islands (Vanuatu). *Proceedings of the National Academy of Sciences, 108*(32), 13019–13022. doi:10.1073/pnas.1102842108

Barnett, J., & Adger, W. N. (2003). Climate dangers and atoll countries. *Climatic Change*, *61*(3), 321–337. doi:10.1023/B:CLIM.0000004559.08755.88

Barnett, J., & Campbell, J. (2010). *Climate change and small island states: Power, knowledge and the South Pacific*. London, UK: Earthscan.

Bassiouni, M., & Oki, D. S. (2012). Trends and shifts in streamflow in Hawaiʻi, 1913–2008. *Hydrological Processes*. doi:10.1002/hyp.9298

Battisti, D. S., & Naylor, R. L. (2009). Historical warnings of future food insecurity with unprecedented seasonal heat. *Science*, *323*(5911), 240–244. doi:10.1126/science.1164363

Becker, M. B., Meyssignac, B., Letetrel, C., Llovel, W., Cazenave, A., & Delcroix, T. (2012). Sea level variations at tropical Pacific islands since 1950. *Global and Planetary Change*, *80–81*, pp. 85–98. doi:10.1016/j.gloplacha.2011.09.004

Bell, J. D., Adams, T. J. H., Johnson, J. E., Hobday, A. J., & Sen Gupta, A. (2011). Pacific communities, fisheries, aquaculture and climate change: An introduction. In J. D. Bell, J. E. Johnson, & A. J. Hobday (Eds.), *Vulnerability of tropical Pacific fisheries and aquaculture to climate change* (pp. 1–48). Noumea, New Caledonia: Secretariat of the Pacific Community.

Benning, T. L., LaPointe, D., Atkinson, C. T., & Vitousek, P. M. (2002). Interactions of climate change with biological invasions and land use in the Hawaiian Islands: Modeling the fate of endemic birds using a geographic information system. *Proceedings of the National Academy of Sciences*, *99*(22), 14246–14249. doi:10.1073/pnas.162372399

Bindoff, N. L., Willebrand, J., Artale, V., Cazenave, A., Gregory, J. M., Gulev, S., Hanawa, K., et al. (2007). Observations: Oceanic climate change and sea level. In S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. Averyt, M. M. B. Tignor, et al. (Eds.), *Climate change 2007: The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 385–432). Cambridge, UK, and New York, NY: Cambridge University Press.

Björk, M., Short, F., Mcleod, E., & Beer, S. (2008). *Managing seagrass for resilience to climate change* (IUCN Resilience Science Group Working Paper Series No. 3). Gland, Switzerland: IUCN. Retrieved from http://www.iucn.org/about/work/programmes/marine/marine_our_work/climate_change/publications.cfm?1613/Managing-Seagrasses-for-Resilience-to-Climate-Change

Bridgman, H. A., & Oliver, J. E. (2006). *The global climate system: Patterns, processes, and teleconnections*. Cambridge, UK, and New York, NY: Cambridge University Press.

Brill, R. W. (1994). A review of temperature and oxygen tolerance studies of tunas pertinent to fisheries oceanography, movement models and stock assessments. *Fisheries Oceanography*, *3*(3), 204–216. doi:10.1111/j.1365-2419.1994.tb00098.x

Brohan, P., Kennedy, J. J., Harris, I., Tett, S. F. B., & Jones, P. D. (2006). Uncertainty estimates in regional and global observed temperature changes: A new data set from 1850. *Journal of Geophysical Research*, *111*, D12106. doi:200610.1029/2005JD006548

Bromirski, P. D., Miller, A. J., Flick, R. E., & Auad, G. (2011). Dynamical suppression of sea level rise along the Pacific coast of North America: Indications for imminent acceleration. *Journal of Geophysical Research*, *116*, C07005. doi:10.1029/2010JC006759

Brown, B. E., Dunne, R. P., Phongsuwan, N., & Somerfield, P. J. (2011). Increased sea level promotes coral cover on shallow reef flats in the Andaman Sea, eastern Indian Ocean. *Coral Reefs*, *30*(4), 867–878. doi:10.1007/s00338-011-0804-9

Bruno, J. F., & Selig, E. R. (2007). Regional decline of coral cover in the Indo-Pacific: Timing, extent, and subregional comparisons. *PLoS ONE*, *2*(8), e711. doi:10.1371/journal.pone.0000711

Bruno, J. F., Siddon, C. E., Witman, J. D., Colin, P. L., & Toscano, M. A. (2001). El Niño related coral bleaching in Palau, Western Caroline Islands. *Coral Reefs*, *20*(2), 127–136. doi:10.1007/s003380100151

Burke, L., Reytar, K., Spalding, M., & Perry, A. (2011). *Reefs at risk revisited*. Washington, DC: World Resources Institute. Retrieved from http://www.wri.org/publication/reefs-at-risk-revisited

Burkett, M. (2011). In search of refuge: Pacific Islands, climate-induced migration, and the legal frontier. *AsiaPacific Issues*, *98*. Retrieved from http://www.eastwestcenter.org/download/3740/32472/api098.pdf

Caccamise, D. J., Merrifield, M. A., Bevis, M., Foster, J., Firing, Y. L., Schenewerk, M. S., Taylor, F. W., et al. (2005). Sea level rise at Honolulu and Hilo, Hawaii: GPS estimates of differential land motion. *Geophysical Research Letters*, *32*, L03607. doi:10.1029/2004GL021380

Caldwell, P. C., Vitousek, S., & Aucan, J. P. (2009). Frequency and duration of coinciding high surf and tides along the north shore of Oahu, Hawaii, 1981–2007. *Journal of Coastal Research*, *25*(3), 734–743. doi:10.2112/08-1004.1

Callaghan, D. P., Nielsen, P., Cartwright, N., Gourlay, M. R., & Baldock, T. E. (2006). Atoll lagoon flushing forced by waves. *Coastal Engineering*, *53*(8), 691–704. doi:10.1016/j.coastaleng.2006.02.006

Cane, M. A. (2005). The evolution of El Niño, past and future. *Earth and Planetary Science Letters*, *230*(3–4), 227–240. doi:10.1016/j.epsl.2004.12.003

Cao, G., Giambelluca, T. W., Stevens, D. E., & Schroeder, T. A. (2007). Inversion variability in the Hawaiian trade wind regime. *Journal of Climate*, *20*(7), 1145–1160. doi:10.1175/JCLI4033.1

Carter, L. M., Shea, E., Hamnett, M., Anderson, C., Dolcemascolo, G., Guard, C., Taylor, M., et al. (2001). Potential consequences of climate variability and change for the US-Affiliated islands of the Pacific and Caribbean. In National Assessment Synthesis Team, *Climate change impacts on the United States: The potential consequences of climate variability and change* (pp. 315–349). Cambridge, UK, and New York, NY: Cambridge University Press. Retrieved from http://www.usgcrp.gov/usgcrp/Library/nationalassessment/11Islands.pdf

Cayan, D. R., Bromirski, P. D., Hayhoe, K., Tyree, M., Dettinger, M. D., & Flick, R. E. (2008). Climate change projections of sea level extremes along the California coast. *Climatic Change*, *87*(Suppl 1), S57–S73. doi:10.1007/s10584-007-9376-7

Cazenave, A., & Llovel, W. (2010). Contemporary sea level rise. *Annual Review of Marine Science*, *2*(1), 145–173. doi:10.1146/annurev-marine-120308-081105

Chavez, F. P., Strutton, P. G., Friederich, G. E., Feely, R. A., Feldman, G. C., Foley, D. G., &

McPhaden, M. J. (1999). Biological and chemical response of the equatorial Pacific Ocean to the 1997-98 El Niño. *Science*, *286*(5447), 2126–2131. doi:10.1126/science.286.5447.2126

Chen, J., Carlson, B. E., & Del Genio, A. D. (2002). Evidence for strengthening of the tropical general circulation in the 1990s. *Science*, *295*(5556), 838–841. doi:10.1126/science.1065835

Chen, J., Del Genio, A. D., Carlson, B. E., & Bosilovich, M. G. (2008). The spatiotemporal structure of twentieth-century climate variations in observations and reanalyses. Part I: Long-term trend. *Journal of Climate*, *21*(11), 2611–2633. doi:10.1175/2007JCLI2011.1

Chen, S., & Qiu, B. (2010). Mesoscale eddies northeast of the Hawaiian Archipelago from satellite altimeter observations. *Journal of Geophysical Research*, *115*, C03016. doi:10.1029/2009JC005698

Cheung, K. F., Phadke, A. C., Wei, Y., Rojas, R., Douyere, Y. J.-M., Martino, C. D., Houston, S. H., et al. (2003). Modeling of storm-induced coastal flooding for emergency management. *Ocean Engineering*, *30*(11), 1353–1386. doi:10.1016/S0029-8018(02)00133-6

Chowdhury, M. R., Barnston, A. G., Guard, C., Duncan, S., Schroeder, T. A., & Chu, P.-S. (2010). Sea-level variability and change in the US-Affiliated Pacific Islands: Understanding the high sea levels during 2006–2008. *Weather*, *65*(10), 263–268. doi:10.1002/wea.468

Christensen, J. H., Hewitson, B., Busuioc, A., Chen, A., Gao, X., Held, I., Jones, R., et al. (2007). Regional climate projections. In S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. Averyt, M. M. B. Tignor, et al. (Eds.), *Climate change 2007: The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 847–940). Cambridge, UK, and New York, NY: Cambridge University Press.

Chu, P.-S. (2002). Large-scale circulation features associated with decadal variations of tropical cyclone activity over the Central North Pacific. *Journal of Climate*, *15*(18), 2678–2689. doi:10.1175/1520-0442(2002)015<2678:LSCFAW>2.0.CO;2

Chu, P.-S., & Chen, H. (2005). Interannual and interdecadal rainfall variations in the Hawaiian Islands. *Journal of Climate*, *18*(22), 4796–4813. doi:10.1175/JCLI3578.1

Chu, P.-S., Chen, Y. R., & Schroeder, T. A. (2010). Changes in precipitation extremes in the Hawaiian Islands in a warming climate. *Journal of Climate*, *23*(18), 4881–4900. doi:10.1175/2010JCLI3484.1

Church, J. A., & White, N. J. (2006). A 20th century acceleration in global sea-level rise. *Geophysical Research Letters*, *33*, L01602. doi:10.1029/2005GL024826

Church, J. A., & White, N. J. (2011). Sea-level rise from the late 19th to the early 21st century. *Surveys in Geophysics*, *32*(4-5), 585–602. doi:10.1007/s10712-011-9119-1

Church, J. A., White, N. J., Coleman, R., Lambeck, K., & Mitrovica, J. X. (2004). Estimates of the regional distribution of sea level rise over the 1950–2000 period. *Journal of Climate*, *17*(13), 2609–2625. doi:10.1175/1520-0442(2004)017<2609:EOTRDO>2.0.CO;2

Church, J. A., White, N. J., & Hunter, J. R. (2006). Sea-level rise at tropical Pacific and Indian Ocean islands. *Global and Planetary Change*, *53*(3), 155–168. doi:10.1016/j.gloplacha.2006.04.001

Church, J. A., White, N. J., Konikow, L. F., Domingues, C. M., Cogley, J. G., Rignot, E., Gregory, J. M., et al. (2011). Revisiting the Earth's sea-level and energy budgets from 1961 to 2008. *Geophysical Research Letters*, *38*, L18601. doi:10.1029/2011GL048794

Codiga, D., & Wager, K. (2011). *Sea-level rise and coastal land use in Hawai'i: A policy tool kit for state and local governments*. Honolulu, HI: Center for Island Climate Adaptation and Policy. Retrieved from http://icap.seagrant.soest.hawaii.edu/sites/seagrant.soest.hawaii.edu/files/publications/icap-sealevelrisetoolkit_web-1_2.pdf

Collins, M., An, S.-I., Cai, W., Ganachaud, A., Guilyardi, E., Jin, F.-F., Jochum, M., et al. (2010). The impact of global warming on the tropical Pacific Ocean and El Niño. *Nature Geoscience*, *3*(6), 391–397. doi:10.1038/ngeo868

Commission on Water Resource Management. (10 June 2010). *'lao ground water management area high-level source water-use permit applications and petition to amend interim instream flow standards of Waihe'e River and Waiehu, 'lao, & Waikapu Streams contested case hearing* (CCH-MAO6-Ol). Retrieved from http://hawaii.gov/dlnr/cwrm/cch/cchma0601/CCHMA0601-02.pdf

Cooper, T. F., De'Ath, G., Fabricius, K. E., & Lough, J. M. (2008). Declining coral calcification in massive Porites in two nearshore regions of the northern Great Barrier Reef. *Global Change Biology*, *14*(3), 529–538. doi:10.1111/j.1365-2486.2007.01520.x

Culver, M. E., Schubel, J. R., Davidson, M. A., Haines, J., & Texeira, K. C. (Eds.). (2010). *Proceedings from the Sea Level Rise and Inundation Community Workshop, 2009 Dec 3-5*. Lansdowne, MD: sponsored by the National Oceanic and Atmospheric Administration and US Geological Survey. Retrieved from http://www.csc.noaa.gov/publications/inundation-workshop.pdf

D'Aleo, J., & Easterbrook, D. (2010). Multidecadal tendencies in ENSO and global temperatures related to multidecadal oscillations. *Energy & Environment*, *21*(5), 437–460. doi:10.1260/0958-305X.21.5.437

De'ath, G., Lough, J. M., & Fabricius, K. E. (2009). Declining coral reef calcification on the Great Barrier Reef. *Science*, *323*(5910), 116–119. doi:10.1126/science.1165283

Denslow, J. S. (2003). Weeds in paradise: Thoughts on the invasibility of tropical islands. *Annals of the Missouri Botanical Garden*, *90*(1), 119–127. Retrieved from http://www.jstor.org/stable/3298531

Deser, C., Phillips, A. S., & Alexander, M. A. (2010a). Twentieth century tropical sea surface temperature trends revisited. *Geophysical Research Letters*, *37*, L10701. doi:10.1029/2010GL043321

Deser, C., Phillips, A., Bourdette, V., & Teng, H. (2010b). Uncertainty in climate change projections: The role of internal variability. *Climate Dynamics*, *38*(3-4), 527–546. doi:10.1007/s00382-010-0977-x

Di Lorenzo, E., Cobb, K. M., Furtado, J. C., Schneider, N., Anderson, B. T., Bracco, A., Alexander, M. A., et al. (2010). Central Pacific El Niño and decadal climate change in the North Pacific Ocean. *Nature Geoscience*, *3*(11), 762–765. doi:10.1038/ngeo984

Diaz, H. F., Chu, P.-S., & Eischeid, J. K. (2005). *Rainfall changes in Hawaii during the last century*. Paper presented at the 16th Conference on Climate Variability and Change, American Meteorological Society, 2005 January 9–13, San Diego, CA. Retrieved from http://ams.confex.com/ams/pdfpapers/84210.pdf

Diaz, H. F., Giambelluca, T. W., & Eischeid, J. K. (2011). Changes in the vertical profiles of mean temperature and humidity in the Hawaiian Islands. *Global and Planetary Change*, *77*(1-2), 21–25. doi:10.1016/j.gloplacha.2011.02.007

Dickinson, W. R. (1998). Geomorphology and geodynamics of the Cook-Austral island-seamount chain in the South Pacific Ocean: Implications for hotspots and plumes. *International Geology Review*, *40*(12), 1039–1075. doi:10.1080/00206819809465254

Dickinson, W. R. (1999). Holocene sea-level record on Funafuti and potential impact of global warming on central Pacific atolls. *Quaternary Research*, *51*(2), 124–132. doi:10.1006/qres.1998.2029.

Dickinson, W. R. (2000). Hydro-isostatic and tectonic influences on emergent Holocene paleoshorelines in the Mariana Islands, western Pacific Ocean. *Journal of Coastal Research*, *16*(3), 735–746. Retrieved from http://www.jstor.org/stable/10.2307/4300083

Dickinson, W. R. (2001). Paleoshoreline record of relative Holocene sea levels on Pacific islands. *Earth-Science Reviews*, *55*(3-4), 191–234. doi:10.1016/S0012-8252(01)00063-0

Dickinson, W. R. (2003). Impact of mid-Holocene hydro-isostatic highstand in regional sea level on habitability of islands in Pacific Oceania. *Journal of Coastal Research*, *19*(3), 489–502. Retrieved from http://www.jstor.org/stable/4299192

Dickinson, W. R. (2009). Pacific atoll living: How long already and until when. *GSA Today*, *19*(3), 4. doi:10.1130/GSATG35A.1

Dickinson, W. R., & Burley, D. V. (2007). Geoarchaeology of Tonga: Geotectonic and geomorphic controls. *Geoarchaeology, 22*(2), 229–259. doi:10.1002/gea.20164.

Dickinson, W. R., Burley, D. V., & Shutler, Jr., R. (1999). Holocene paleoshoreline record in Tonga: Geomorphic features and archaeological implications. *Journal of Coastal Research*, *15*, 682–700.

DiNezio, P. N., Clement, A. C., Vecchi, G. A., Soden, B. J., Kirtman, B. P., & Lee, S.-K. (2009). Climate response of the equatorial Pacific to global warming. *Journal of Climate*, *22*(18), 4873–4892. doi:10.1175/2009JCLI2982.1

Döll, P. (2002). Impact of climate change and variability on irrigation requirements: A global perspective. *Climatic Change*, *54*(3), 269–293. doi:10.1023/A:1016124032231

Doney, S. C., Ruckelshaus, M., Emmett Duffy, J., Barry, J. P., Chan, F., English, C. A., Galindo, H. M., et al. (2012). Climate change impacts on marine ecosystems. *Annual Review of Marine Science*, *4*(1), 11–37. doi:10.1146/annurev-marine-041911-111611

Donner, S. D. (2009). Coping with Commitment: Projected thermal stress on coral reefs under different future scenarios. *PLoS ONE*, *4*(6), e5712. doi:10.1371/journal.pone.0005712

Donner, S. D. (2011). An evaluation of the effect of recent temperature variability on the prediction of coral bleaching events. *Ecological Applications, 21*(5), 1718–1730. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/21830713

Easterling, W. E., Aggarwal, P., Batima, P., Brander, K., Erda, L., Howden, S. M., Kirilenko, A., et al. (2007). Food, fibre, and forest products. In M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden, & C. E. Hanson (Eds.), *Climate change 2007: Impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 273–313). Cambridge, UK, and New York, NY: Cambridge University Press.

Eiben, J. A., & Rubinoff, D. (2010). Life history and captive rearing of the Wekiu bug (Nysius wekiuicola, Lygaeidae), an alpine carnivore endemic to the Mauna Kea volcano of Hawaii. *Journal of Insect Conservation*, *14*(6), 701–709. doi:10.1007/s10841-010-9298-y

Elison Timm, Oliver, & Diaz, H. F. (2009). Synoptic-statistical approach to regional downscaling of IPCC twenty-first-century climate projections: Seasonal rainfall over the Hawaiian Islands. *Journal of Climate*, *22*(16), 4261–4280. doi:10.1175/2009JCLI2833.1

Elison Timm, O., Diaz, H. F., Giambelluca, T. W., & Takahashi, M. (2011). Projection of changes in the frequency of heavy rain events over Hawaii based on leading Pacific climate modes. *Journal of Geophysical Research*, *116*, D04109. doi:10.1029/2010JD014923

Ellison, J. C. (2000). How South Pacific mangroves may respond to predicted climate change and sea level rise. In A. Gillespie & W. C. G. Burns (Eds.), *Climate change in the South Pacific: Impacts and responses in Australia, New Zealand, and Small Island States*, Advances in Global Change Research (Vol. 2, pp. 289–301). Dordrecht, The Netherlands: Kluwer Academic Publishers.

Emanuel, K. (2005). Increasing destructiveness of tropical cyclones over the past 30 years. *Nature*, *436*(7051), 686–688. doi:10.1038/nature03906

Engels, M. S., Fletcher, C. H., Field, M. E., Storlazzi, C. D., Grossman, E. E., Rooney, J. J. B., Conger, C. L., et al. (2004). Holocene reef accretion: Southwest Molokai, Hawaii, U.S.A. *Journal of Sedimentary Research*, *74*(2), 255–269. doi:10.1306/073003740255

Fabricius, K. E., Langdon, C., Uthicke, S., Humphrey, C., Noonan, S., De'ath, G., Okazaki, R., Muehllehner, N., Glas, M. S., & Lough, J. M. (2011). Losers and winners in coral reefs acclimatized to elevated carbon dioxide concentrations. *Nature Climate Change, 1*, 165–169. doi:10.1038/nclimate1122

Fan, Y., Lin, S.-J., Held, I. M., Yu, Z., & Tolman, H. L. (2012). Global ocean surface wave simulation using a coupled atmosphere-wave model. *Journal of Climate*, *25*(18), 6233–6252. doi:10.1175/JCLI-D-11-00621.1

Feely, R., Doney, S., & Cooley, S. (2009). Ocean acidification: Present conditions and future changes in a high-CO2 world. *Oceanography*, *22*(4), 36–47. doi:10.5670/oceanog.2009.95

Feng, M., Li, Y., & Meyers, G. (2004). Multidecadal variations of Fremantle sea level: Footprint of climate variability in the tropical Pacific. *Geophysical Research Letters*, *31*, L16302. doi:10.1029/2004GL019947

Feng, M., McPhaden, M. J., & Lee, T. (2010). Decadal variability of the Pacific subtropical cells and their influence on the southeast Indian Ocean. *Geophysical Research Letters*, *37*, L09606. doi:10.1029/2010GL042796

Fenner, D., & Heron, S. F. (2008). Annual summer bleaching of a multi-species coral community in backreef pools of American Samoa: A window on the future? *Proceedings of the 11th International Coral Reef Symposium, 2008 July 7-11* (pp. 1289–1293). Ft. Lauderdale, FL. Retrieved from http://www.nova.edu/ncri/11icrs/proceedings/files/m25-04.pdf

Field, C. D. (1995). Impact of expected climate change on mangroves. *Hydrobiologia*, *295*(1-3), 75–81. doi:10.1007/BF00029113

Field, M. E., Ogston, A. S., & Storlazzi, C. D. (2011). Rising sea level may cause decline of fringing coral reefs. *Eos, Transactions, American Geophysical Union*, *92*(33), 273–274. doi:10.1029/2011EO330001

Firing, Y. L., & Merrifield, M. A. (2004). Extreme sea level events at Hawaii: Influence of mesoscale eddies. *Geophysical Research Letters*, *31*, L24306. doi:10.1029/2004GL021539

Firing, Y. L., Merrifield, M. A., Schroeder, T. A., & Qiu, B. (2004). Interdecadal sea level fluctuations at Hawaii. *Journal of Physical Oceanography*, *34*(11), 2514–2524. doi:10.1175/JPO2636.1

Fletcher, C. H., & Richmond, B. M. (2010). *Climate change in the Federated States of Micronesia: Food and water security, climate risk management, and adaptive strategies*. Honolulu, HI: University of Hawai'i Sea Grant College Program. Retrieved from http://seagrant.soest.hawaii.edu/sites/seagrant.soest.hawaii.edu/files/publications/1webfinal_maindocument_climatechangefsm.pdf

Fletcher, C. H., Richmond, B. M., Barnes, G. M., & Schroeder, T. A. (1995). Marine flooding on the coast of Kaua'i during Hurricane Iniki: Hindcasting inundation components and delineating washover. *Journal of Coastal Research*, *11*(1), 188–204. Retrieved from http://www.jstor.org/stable/10.2307/4298321

Flint, B., Leary, P., & Klavitter, J. (2011). Briefing paper to the US delegation to the Agreement on the Conservation of Albatrosses and Petrels (ACAP) presented at the Population Status and Trends and Breeding Sites Working Group meeting, Guayaquil, Ecuador.

Ford, M., Becker, J. M., & Merrifield, M. A. (2012). Case studies of atoll island inundation: Implications of higher sea level on Majuro Atoll, Republic of the Marshall Islands. Unpublished manuscript.

Fox-Rabinovitz, M., Cote, J., Dugas, B., Deque, M., McGregor, J. L., & Belochitski, A. (2008). Stretched-grid model intercomparison project: Decadal regional climate simulations with enhanced variable and uniform-resolution GCMs. *Meteorology and Atmospheric Physics*, *100*(1-4), 159–178. doi:10.1007/s00703-008-0301-z

Frazier, A. G., Diaz, H. F., & Giambelluca, T. W. (2011). *Rainfall in Hawai'i: Spatial and temporal changes since 1920 (Abstract #GC21B-0900)*. Poster presented at the American Geophysical Union Fall Meeting, San Francisco, CA.

Frederiksen, M., Harris, M. P., Daunt, F., Rothery, P., & Wanless, S. (2004). Scale-dependent climate signals drive breeding phenology of three seabird species. *Global Change Biology*, *10*(7), 1214–1221. doi:10.1111/j.1529-8817.2003.00794.x

Freed, L. A., Cann, R. L., Goff, M. L., Kuntz, W. A., & Bodner, G. R. (2005). Increase in avian malaria at upper elevation in Hawaiʻi. *The Condor*, *107*(4), 753. doi:10.1650/7820.1

Gegeo, D. W. (2001). Cultural Rupture and Indigeneity: The Challenge of (Re)visioning "Place" in the Pacific. *The Contemporary Pacific*, *13*(2), 491–507. Retrieved from http://scholarspace.manoa.hawaii.edu/handle/10125/13580

Gegeo, D. W., & Watson-Gegeo, K. A. (2001). "How We Know": Kwara'ae Rural Villagers Doing Indigenous Epistemology. *The Contemporary Pacific*, *13*(1), 55–88. Retrieved from http://scholarspace.manoa.hawaii.edu/handle/10125/13317

Gemmrich, J., Thomas, B., & Bouchard, R. (2011). Observational changes and trends in northeast Pacific wave records. *Geophysical Research Letters*, *38*, L22601. doi:10.1029/2011GL049518

Genz, A., Merrifield, M. A., Kontoes, C., & Marra, J. J. (2012). Annual extreme water levels from tide gauges: Contributing factors and geographic patterns. Unpublished manuscript.

Giambelluca, T. W., Chen, Q., Frazier, A. G., Price, J. P., Chen, Y.-L., Chu, P.-S., Eischeid, J., et al. (2011). *The rainfall atlas of Hawaiʻi*. Retrieved from http://rainfall.geography.hawaii.edu

Giambelluca, T. W., Diaz, H. F., & Luke, M. S. A. (2008). Secular temperature changes in Hawai'i. *Geophysical Research Letters*, *35*, L12702. doi:10.1029/2008GL034377

Gilman, E. L., Ellison, J., Duke, N. C., & Field, C. (2008). Threats to mangroves from climate change and adaptation options: A review. *Aquatic Botany*, *89*(2), 237–250. doi:10.1016/j.aquabot.2007.12.009

Gingerich, S. B., & Oki, D. S. (2000). *Ground water in Hawaii* (US Geological Survey Fact Sheet No. 126-00). Retrieved from http://hi.water.usgs.gov/publications/pubs/fs/fs126-00.pdf

Gingerich, S. B., & Wolff, R. H. (2005). *Effects of surface-water diversions on habitat availability for native macrofauna, northeast Maui, Hawaii* (US Geological Survey Scientific Investigations Report 2005-5213). Retrieved from http://pubs.usgs.gov/sir/2005/5213/

Giorgi, F. (2005). Climate change prediction. *Climatic Change*, *73*(3), 239–265. doi:10.1007/s10584-005-6857-4

Giorgi, F., & Francisco, R. (2000). Evaluating uncertainties in the prediction of regional climate change. *Geophysical Research Letters*, *27*(9), 1295–1298. doi:10.1029/1999GL011016

Goddard, L., Mason, S. J., Zebiak, S. E., Ropelewski, C. F., Basher, R., & Cane, M. A. (2001). Current approaches to seasonal to interannual climate predictions. *International Journal of Climatology*, *21*(9), 1111–1152. doi:10.1002/joc.636

Grantham, H. S., McLeod, E., Brooks, A., Jupiter, S. D., Hardcastle, J., Richardson, A. J., Poloczanska, E. S., et al. (2011). Ecosystem-based adaptation in marine ecosystems of tropical Oceania in response to climate change. *Pacific Conservation Biology*, *17*(3), 241. Retrieved from http://search.informit.com.au/documentSummary;dn=663850795411036;res=IELHSS

Graves, M. W., & Addison, D. J. (1995). The Polynesian settlement of the Hawaiian Archipelago: Integrating models and methods in archaeological interpretation. *World Archaeology*, *26*(3), 380–399. doi: 10.1080/00438243.1995.9980283

Gray, R. D., Drummond, A. J., & Greenhill, S. J. (2009). Language phylogenies reveal expansion pulses and pauses in Pacific settlement. *Science*, *323*(5913), 479–483. doi:10.1126/science.1166858

Grinsted, A., Moore, J. C., & Jevrejeva, S. (2010). Reconstructing sea level from paleo and projected temperatures 200 to 2100 AD. *Climate Dynamics*, *34*(4), 461–472. doi:10.1007/s00382-008-0507-2

Grossman, E. E., Fletcher, C. H., & Richmond, B. M. (1998). The Holocene sea-level highstand in the equatorial Pacific: Analysis of the insular paleosea-level database. *Coral Reefs*, *17*(3), 309–327. doi:10.1007/s003380050132

Group 70 International. (2009). *Ko 'olau Loa Watershed Management Plan: O 'ahu Water Management Plan* (Prepared for the Honolulu Board of Water Supply). Honolulu, HI.

Gualdi, S., Scoccimarro, E., & Navarra, A. (2008). Changes in tropical cyclone activity due to global warming: Results from a high-resolution coupled general circulation model. *Journal of Climate*, *21*(20), 5204–5228. doi:10.1175/2008JCLI1921.1

Hamlin, S. N., & Takasaki, K. J. (1996). *Water-quality reconnaissance of ground-water in the inhabited outer islands of Chuuk State, Federated States of Micronesia, 1984-85* (US Geological Survey Water-Resources Investigations Report No. 96-4180). Retrieved from http://pubs.er.usgs.gov/usgspubs/wri/wri964180

Hawai'i County. (2010, August). Hawai'i County water use and development plan update. Retrieved from http://hawaii.gov/dlnr/cwrm/planning/wudpha2012.pdf

Hawai'i State Civil Defense. (2010). State of Hawai'i multi-hazard mitigation plan, 2010 update. Retrieved from http://www.scd.hawaii.gov/2010_hmp.html

Hawai'i State Department of Business, Economic Development & Tourism. (2011). *Quarterly statistical and economic report, 4th quarter 2011*. Retrieved from http://hawaii.gov/dbedt/info/economic/data_reports/qser/archive-qser/qser-2011q4.pdf

Hawai'i Tourism Authority. (2011). *2011 annual report to the Hawai'i state legislature*. Retrieved from http://www.hawaiitourismauthority.org/default/assets/File/HTA_AR2011_Final.pdf

Hawkins, E., & Sutton, R. (2010). The potential to narrow uncertainty in projections of regional precipitation change. *Climate Dynamics*, *37*(1-2), 407–418. doi:10.1007/s00382-010-0810-6

Held, I. M., & Soden, B. J. (2006). Robust responses of the hydrological cycle to global warming. *Journal of Climate*, *19*(21), 5686–5699. doi:10.1175/JCLI3990.1

Hemer, M. A., Wang, X. L., Church, J. A., & Swail, V. R. (2010). Modeling proposal: Coordinating global ocean wave climate projections. *Bulletin of the American Meteorological Society*, *91*(4), 451–454. doi:10.1175/2009BAMS2951.1

Hemer, M.A., Katzfey, J. & Trenham, C. (2012a). Global dynamical projections of surface ocean wave climate for a future high greenhouse gas emission scenario. Manuscript submitted for publication.

Hemer, M. A., Fan, Y., Mori, N., Semedo, A., & Wang, X. L. (2012b). Projected future changes in wind-wave climate in a multi-model ensemble. Manuscript submitted for publication.

Henry, R., & Jeffery, W. (2008). Waterworld: The heritage dimensions of climate change in the Pacific. *Historic Environment*, *21*(1), 12–18. Retrieved from http://www.aicomos.com/wp-content/uploads/rositahenry.pdf

Hezel, F. X. (2009). High water in the low atolls. *Micronesian Counselor*, *#76*. Retrieved from http://www.micsem.org/pubs/counselor/frames/highwaterfr.htm

Hoegh-Guldberg, O. (1999). Climate change, coral bleaching and the future of the world's coral reefs. *Marine and Freshwater Research*, *50*(8), 839. doi:10.1071/MF99078

Hoegh-Guldberg, O., Andréfouët, S., Fabricius, K. E., Diaz-Pulido, G., Lough, J. M., Marshall, P. A., & Pratchett, M. S. (2011). Vulnerability of coral reefs in the tropical Pacific to climate change. In J.D. Bell, J. E. Johnson, & A. J. Hobday (Eds.), *Vulnerability of tropical Pacific fisheries and aquaculture to climate change* (pp. 251–296). Noumea, New Caledonia: Secretariat of the Pacific Community. Retrieved from http://www.publish.csiro.au/nid/126/paper/MF99078.htm

Holgate, S. J. (2007). On the decadal rates of sea level change during the twentieth century. *Geophysical Research Letters*, *34*, L01602. doi:10.1029/2006GL028492

Hunt, C. D. (1996). *Geohydrology of the island of Oahu, Hawaii* (US Geological Survey Professional Paper No. 1412-B). Retrieved from http://pubs.er.usgs.gov/publication/pp1412B

Hunter, J. (2012). A simple technique for estimating an allowance for uncertain sea-level rise. *Climatic Change*, *113*(2), 239–252. doi:10.1007/s10584-011-0332-1

International Organization for Migration. (2009). *Compendium of IOM's activities in migration, climate change and the environment*. Geneva, Switzerland: IOM. IPCC. (2007). *Climate change 2007: The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. (S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. Averyt, M. M. B. Tignor, et al., Eds.). Cambridge, UK, and New York, NY: Cambridge University Press.

IPCC. (2001). *Climate change 2001: Synthesis report. A contribution of Working Groups I, II, and III to the Third Assessment Report of the Intergovernmental Panel on Climate Change* (R. T. Watson and the Core Writing Team (Eds.). Cambridge, UK, and New York, NY: Cambridge University Press.

IPCC. (2007). *Climate change 2007: The physical science basis. A contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. (S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. Averyt, M. M. B. Tignor, et al. [Eds.]) Cambridge, UK, and New York, NY: Cambridge University Press. Retrieved from http://www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_wg1_report_the_physical_science_basis.htm

Irving, D. B., Perkins, S. E., Brown, J. R., Gupta, A. S., Moise, A. F., Murphy, B. F., Muir, L. C., et al. (2011). Evaluating global climate models for the Pacific island region. *Climate Research*, *49*(3), 169–187. doi:10.3354/cr01028

Izuka, S. K. (2011). *Potential effects of roadside dry wells on groundwater quality on the island of Hawai'i: Assessment using numerical groundwater models* (US Geological Survey Scientific Investigations Report No. 2011–5072). Retrieved from http://pubs.usgs.gov/sir/2011/5072/

Izuka, S. K., Giambelluca, T. W., & Nullet, M. A. (2005). *Potential evapotranspiration on Tutuila, American Samoa* (US Geological Survey Scientific Investigations Report No. 2005-5200). Retrieved from http://pubs.usgs.gov/sir/2005/5200/

Jacklick, L. Z., White, R., & Lobwik, N. (2011). *The observed climate, climate variability and change of Majuro Atoll, Republic of the Marshall Islands*. Poster developed for the Greenhouse 2011 Conference. Retrieved from http://www.cawcr.gov.au/projects/PCCSP/pdf/5.Marshall_GH_Poster.pdf

Jevrejeva, S., Moore, J. C., Grinsted, A., & Woodworth, P. L. (2008). Recent global sea level acceleration started over 200 years ago? *Geophysical Research Letters*, *35*, L08715. doi:200810.1029/2008GL033611

Jones, P. D., New, M., Parker, D. E., Martin, S., & Rigor, I. G. (1999). Surface air temperature and its changes over the past 150 years. *Reviews of Geophysics*, *37*(2), 173–199. doi:10.1029/1999RG900002

Kamiguchi, K., Kitoh, A., Uchiyama, T., Mizuta, R., & Noda, A. (2006). Changes in precipitation-based extremes indices due to global warming projected by a global 20-km-mesh atmospheric model. *SOLA*, *2*, 64–67. doi:10.2151/sola.2006-017

Karl, T. R., Diamond, H. J., Bojinski, S., Butler, J. H., Dolman, H., Haeberli, W., Harrison, D. E., et al. (2010). Observation needs for climate information, prediction and application: Capabilities of existing and future observing systems. *Procedia Environmental Sciences*, *1*, 192–205. doi:10.1016/j.proenv.2010.09.013

Kawabe, M. (2000). Calculation of interannual variations of sea level in the subtropical North Pacific. *Journal of Oceanography*, *56*(6), 691–706. doi:10.1023/A:1011129801210

Kawaharada, D. (2011). The settlement of Polynesia, part 1. Retrieved from http://www.pvs-hawaii.com/History_Culture/settlement_part1.htm

Keith, P. (2003). Biology and ecology of amphidromous Gobiidae of the Indo-Pacific and the Caribbean regions. *Journal of Fish Biology*, *63*(4), 831–847. doi:10.1046/j.1095-8649.2003.00197.x

Kiladis, G. N., & Diaz, H. F. (1989). Global climatic anomalies associated with extremes in the Southern Oscillation. *Journal of Climate*, *2*(9), 1069–1090. doi:10.1175/1520-0442(1989)002<1069:GCAAWE>2.0.CO;2

Kilpatrick, A. M. (2006). Facilitating the evolution of resistance to avian malaria in Hawaiian birds. *Biological Conservation*, *128*(4), 475–485. doi:10.1016/j.biocon.2005.10.014

Kilpatrick, A. M., LaPointe, D. A., Atkinson, C. T., Woodworth, B. L., Lease, J. K., Reiter, M. E., Gross, K., et al. (2006). Effects of chronic avian malaria (Plasmodium relictum) infection on reproductive success of Hawaii Amakihi (Hemignathus virens). *The Auk*, *123*(3), 764–774. doi:10.1642/0004-8038(2006)123[764:EOCAMP]2.0.CO;2

Kinzie, R. A., Chong, C., Deverell, J., Lindstrom, D., & Wolff, R. H. (2006). Effects of water removal on a Hawaiian stream ecosystem. *Pacific Science*, *60*(1), 1–47. doi: 10.1353/psc.2005.0058

Knapp, K. R., Kruk, M. C., Levinson, D. H., Diamond, H. J., & Neumann, C. J. (2010). The International Best Track Archive for Climate Stewardship (IBTrACS). *Bulletin of the American Meteorological Society*, *91*(3), 363–376. doi:10.1175/2009BAMS2755.1

Knutson, T. R., McBride, J. L., Chan, J., Emanuel, K., Holland, G., Landsea, C., Held, I., et al. (2010). Tropical cyclones and climate change. *Nature Geoscience*, *3*(3), 157–163. doi:10.1038/ngeo779

Knutti, R., & Hegerl, G. C. (2008). The equilibrium sensitivity of the Earth's temperature to radiation changes. *Nature Geoscience*, *1*(11), 735–743. doi:10.1038/ngeo337

Kodama, K. R., & Businger, S. (1998). Weather and forecasting challenges in the Pacific region of the National Weather Service. *Weather and Forecasting*, *13*(3), 523–546. doi:10.1175/1520-0434(1998)013<0523:WAFCIT>2.0.CO;2

The Kohala Center. (2008). Kahalu'u Bay Education Center. Retrieved from http://www.kohala-center.org/kahaluubay/about.html

Kolivras, K. N. (2010). Changes in dengue risk potential in Hawaii, USA, due to climate variability and change. *Climate Research*, *42*(1), 1–11. doi:10.3354/cr00861

Krushelnycky, P., Loope, L., Starr, F., Starr, K., & Giambelluca, T. (2011). Is climate change already impacting Haleakalā silverswords? Presented at the 19th Annual Hawaii Conservation Conference, 2-4 August 2011, Honolulu, HI. Retrieved from http://hawaii.conference-services.net/reports/template/onetextabstract.xml?xsl=template/onetextabstract.xsl&conferenceID=2468&abstractID=512083

Kruk, M. C., & Levinson, D. H. (2008). *Evaluating the impacts of climate change on rainfall extremes for Hawaii and coastal Alaska*. Paper presented at the 24th Conference on Severe Local Storms, American Meteorological Society, 27–31 October 2008, Savannah, GA. Retrieved from http://ams.confex.com/ams/24SLS/techprogram/paper_142172.htm

Kruk, M. C., Marra, J. J., Ruggiero, P., Atkinson, D., Merrifield, M., Levinson, D., & Lander, M. (2012). Pacific Storms Climatology Products (PSCP): Understanding Extreme Events. *Bulletin of the American Meteorological Society*. doi:10.1175/BAMS-D-11-00075.1

Kug, J.-S., Jin, F.-F., & An, S.-I. (2009). Two types of El Niño events: Cold tongue El Niño and warm pool El Niño. *Journal of Climate*, *22*(6), 1499–1515. doi:10.1175/2008JCLI2624.1

Kumar, A., & Hoerling, M. P. (1998). Annual cycle of Pacific–North American seasonal predictability associated with different phases of ENSO. *Journal of Climate*, *11*(12), 3295–3308. doi:10.1175/1520-0442(1998)011<3295:ACOPNA>2.0.CO;2

Lal, M., McGregor, J. L., & Nguyen, K. C. (2007). Very high-resolution climate simulation over Fiji using a global variable-resolution model. *Climate Dynamics*, *30*(2-3), 293–305. doi:10.1007/s00382-007-0287-0

Lander, M. A. (1994). *Meteorological factors associated with drought on Guam* (Technical Report No. 75). University of Guam, Water and Environmental Research Institute of the Western Pacific. Retrieved from http://www.weriguam.org/reports/item/meteorological-factors-associated-with-drought-on-guam

Lander, M. A. (2004). *Rainfall climatology for Saipan: Distribution, return-periods, El Niño, tropical cyclones, and long-term variations* (Technical Report No. 103). University of Guam, Water and Environmental Research Institute of the Western Pacific. Retrieved from http://www.weriguam.org/reports/item/rainfall-climatology-for-saipan-distribution-return-periods-el-nino-tropical-cyclones-and-long-term-variations

Lander, M. A., & Guard, C. P. (2003). *Creation of a 50-year rainfall database, annual rainfall climatology, and annual rainfall distribution map for Guam* (Technical Report No. 102). University of Guam, Water and Environmental Research Institute of the Western Pacific. Retrieved from http://www.weriguam.org/reports/item/creation-of-a-50-year-rainfall-database-annual-rainfall-climatology-and-annual-rainfall-distribution-map-for-guam

Lander, M. A., & Khosrowpanah, S. (2004). *A rainfall climatology for Pohnpei Islands, the Federated States of Micronesia* (Technical Report No. 100). University of Guam, Water and Environmental Research Institute of the Western Pacific. Retrieved from http://www.weriguam.org/reports/item/rainfall-climatology-for-pohnpei-islands-federated-states-of-micronesia

Langdon, C., & Atkinson, M. J. (2005). Effect of elevated pCO2 on photosynthesis and calcification of corals and interactions with seasonal change in temperature/irradiance and nutrient enrichment. *Journal of Geophysical Research*, *110*, C09S07. doi:10.1029/2004JC002576

LaPonte, D., & Burgett, J. (2005). *Mosquitoes in Hawai'i* (Position Paper No. 2005-02). Honolulu, HI: Hawai'i Conservation Alliance. Retrieved from http://hawaiiconservation.org/files/content/resources/publications/position_papers/mosquitos.pdf

Le Borgne, R., Allain, V., Griffiths, S. P., Matear, R. J., McKinnon, A. D., Richardson, A. J., & Young, J. W. (2011). Vulnerability of open ocean food webs in the tropical Pacific to climate change. In J. D. Bell, J. E. Johnson, & A. J. Hobday (Eds.), *Vulnerability of tropical Pacific fisheries and aquaculture to climate change* (pp. 189–250). Noumea, New Caledonia: Secretariat of the Pacific Community.

Lee, T., & McPhaden, M. J. (2010). Increasing intensity of El Niño in the central-equatorial Pacific. *Geophysical Research Letters*, *37*, L14603. doi:10.1029/2010GL044007

Lehodey, Patrick. (2001). The pelagic ecosystem of the tropical Pacific Ocean: Dynamic spatial modelling and biological consequences of ENSO. *Progress in Oceanography*, *49*(1-4), 439–468. doi:10.1016/S0079-6611(01)00035-0

Lehodey, P., Bertignac, M., Hampton, J., Lewis, A., & Picaut, J. (1997). El Niño Southern Oscillation and tuna in the western Pacific. *Nature*, *389*(6652), 715–718. doi:10.1038/39575

Lehodey, P., Hampton, J., Brill, R. W., Nicol, S., Senina, I., Calmettes, B., Pörtner, H. O., et al. (2011). Vulnerability of oceanic fisheries in the tropical Pacific to climate change. In J. D. Bell, J. E. Johnson, & A. J. Hobday (Eds.), *Vulnerability of tropical Pacific fisheries and aquaculture to climate change* (pp. 433–492). Noumea, New Caledonia: Secretariat of the Pacific Community.

Leuliette, E. W., & Miller, L. (2009). Closing the sea level rise budget with altimetry, Argo, and GRACE. *Geophysical Research Letters*, *36*, L04608. doi:10.1029/2008GL036010

Leuliette, E., & Willis, J. (2011). Balancing the sea level budget. *Oceanography*, *24*(2), 122–129. doi:10.5670/oceanog.2011.32

Lewis, N. (2012). Islands in a sea of change: Climate change, health and human security in Small Island States. In H. J. S. Fernando, Z. Klaić, & J. L. McCulley (Eds.), *National security and human health implications of climate change*, NATO Science for Peace and Security Series C: Environmental Security (pp. 13–24). Dordrecht, The Netherlands: Springer.

Li, G., & Ren, B. (2011). Evidence for strengthening of the tropical Pacific Ocean surface wind speed during 1979–2001. *Theoretical and Applied Climatology*, *107*(1-2), 59–72. doi:10.1007/s00704-011-0463-3

Li, T., Kwon, M., Zhao, M., Kug, J.-S., Luo, J.-J., & Yu, W. (2010). Global warming shifts Pacific tropical cyclone location. *Geophysical Research Letters*, *37*, L21804. doi:10.1029/2010GL045124

Lili'uokalani. (1997). *The Kumulipo: An Hawaiian creation myth.* Kentfield, CA: Pueo Press.

Litton, C. M., Sandquist, D. R., & Cordell, S. (2006). Effects of non-native grass invasion on aboveground carbon pools and tree population structure in a tropical dry forest of Hawaii. *Forest Ecology and Management, 231*, 105–113. doi:10.1016/j.foreco.2006.05.008

Loope, L. L., & Crivellone, C. F. (1986). *Status of the Haleakalā silversword: Past and present* (Technical Report No. 58). University of Hawaii, Cooperative National Park Resource Studies Unit.

Lu, H.-J., Lee, K.-T., Lin, H.-L., & Liao, C.-H. (2001). Spatio-temporal distribution of yellowfin tuna *Thunnus albacares* and bigeye tuna *Thunnus obesus* in the Tropical Pacific Ocean in relation to large-scale temperature fluctuation during ENSO episodes. *Fisheries Science*, *67*(6), 1046–1052. doi:10.1046/j.1444-2906.2001.00360.x

Maclellan, N. (2009). *The future is here: Climate change in the Pacific*. Oxfam Briefing Paper. Oxfam Australia & Oxfam New Zealand. Retrieved from http://resources.oxfam.org.au/pages/view.php?ref=390&k=

Madden, R. A. (1976). Estimates of the natural variability of time-averaged sea-level pressure. *Monthly Weather Review*, *104*(7), 942–952. doi:10.1175/1520-0493(1976)104<0942:EOTNVO>2.0.CO;2

Manton, M. J., Belward, A., Harrison, D. E., Kuhn, A., Lefale, P., Rösner, S., Simmons, A., et al. (2010). Observation needs for climate services and research. *Procedia Environmental Sciences*, *1*, 184–191. doi:10.1016/j.proenv.2010.09.012

Mantua, N. J., Hare, S. R., Zhang, Y., Wallace, J. M., & Francis, R. C. (1997). A Pacific interdecadal climate oscillation with impacts on salmon production. *Bulletin of the American Meteorological Society*, *78*(6), 1069–1079. doi:10.1175/1520-0477(1997)078<1069:APICOW>2.0.CO;2

Marra, J. J., Allen, T., Easterling, D., Fauver, S., Karl, T., Levinson, D., Marcy, D., et al. (2007). An integrating architecture for coastal inundation and erosion program planning and product development. *Marine Technology Society Journal*, *41*(1), 62–75. doi:10.4031/002533207787442321

Marshall Islands drought assistance continues. (1998, April 7). *Pacific Islands Report*. Retrieved from http://archives.pireport.org/archive/1998/april/04-08-02.htm

Maue, R. N. (2011). Recent historically low global tropical cyclone activity. *Geophysical Research Letters*, *38*, L14803. doi:10.1029/2011GL047711

McGregor, S., Sen Gupta, A., & England, M. H. (2012). Constraining wind stress products with sea surface height observations and implications for Pacific Ocean sea-level trend attribution. *Journal of Climate*, 120608133708009. doi:10.1175/JCLI-D-12-00105.1

Meehl, G. A., Hu, A., & Santer, B. D. (2009). The mid-1970s climate shift in the Pacific and the relative roles of forced versus inherent decadal variability. *Journal of Climate*, *22*(3), 780–792. doi:10.1175/2008JCLI2552.1

Meehl, G. A., Stocker, T. F., Collins, W. D., Friedlingstein, P., Gaye, A. T., Gregory, J. M., Kitoh, A., et al. (2007). Global climate projections. In S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. Averyt, M. M. B. Tignor, et al. (Eds.), *Climate change 2007: The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 747–845). Cambridge, UK, and New York, NY: Cambridge University Press.

Mendelsohn, R., Emanuel, K., Chonabayashi, S., & Bakkensen, L. (2012). The impact of climate change on global tropical cyclone damage. *Nature Climate Change*, *2*(3), 205–209. doi:10.1038/nclimate1357

Menéndez, M., Méndez, F. J., Losada, I. J., & Graham, N. E. (2008). Variability of extreme wave heights in the northeast Pacific Ocean based on buoy measurements. *Geophysical Research Letters*, *35*(22), L22607. doi:10.1029/2008GL035394

Menéndez, M., & Woodworth, P. L. (2010). Changes in extreme high water levels based on a quasi-global tide-gauge data set. *Journal of Geophysical Research*, *115*, C10011. doi:10.1175/2011JCLI3932.1

Meng, Q., Latif, M., Park, W., Keenlyside, N., Semenov, V., & Martin, T. (2012). Twentieth century Walker Circulation change: Data analysis and model experiments. *Climate Dynamics*, *38*(9), 1757–1773. doi:10.1007/s00382-011-1047-8

Menne, M. J., Williams, C. N., & Palecki, M. A. (2010). On the reliability of the U.S. surface temperature record. *Journal of Geophysical Research*, *115*, D11108. doi:10.1029/2009JD013094

Merrifield, M. A. (2011). A shift in Western Tropical Pacific sea level trends during the 1990s. *Journal of Climate*, *24*(15), 4126–4138. doi:10.1175/2011JCLI3932.1

Merrifield, M. A., Genz, A., Kontoes, C., & Marra, J. J. (2012). Annual extreme water levels from tide gauges: Contributing factors and geographic patterns. In review.

Merrifield, M. A., Merrifield, S. T., & Mitchum, G. T. (2009). An anomalous recent acceleration of global sea level rise. *Journal of Climate*, *22*(21), 5772–5781. doi:10.1175/2009JCLI2985.1

Merrifield, Mark A., & Maltrud, M. E. (2011). Regional sea level trends due to a Pacific trade wind intensification. *Geophysical Research Letters*, *38*, L21605. doi:10.1029/2011GL049576

Miller, K. A. (2007). Climate variability and tropical tuna: Management challenges for highly migratory fish stocks. *Marine Policy*, *31*(1), 56–70. doi:10.1016/j.marpol.2006.05.006

Miller, L. D., Oki, D. S., & Izuka, S. K. (2012). *Trends in annual streamflow and precipitation at sites in the Pacific Islands, 1950–2010*. Unpublished manuscript.

Milly, P. C. D., Betancourt, J., Falkenmark, M., Hirsch, R. M., Kundzewicz, Z. W., Lettenmaier, D. P., & Stouffer, R. J. (2008). Stationarity is dead: Whither water management? *Science*, *319*(5863), 573–574. doi:10.1126/science.1151915

Mitchum, G. T. (1995). The source of 90-day oscillations at Wake Island. *Journal of Geophysical Research*, *100*(C2), 2459–2475. doi:199510.1029/94JC02923

Montaggioni, L. F. (2005). History of Indo-Pacific coral reef systems since the last glaciation: Development patterns and controlling factors. *Earth-Science Reviews*, *71*(1–2), 1–75. doi:10.1016/j.earscirev.2005.01.002

Montenegro, A., Spence, P., Meissner, K. J., Eby, M., Melchin, M. J., & Johnston, S. T. (2011). Climate simulations of the Permian-Triassic boundary: Ocean acidification and the extinction event. *Paleoceanography*, *26*, PA3207. doi:10.1029/2010PA002058

Mori, N., Yasuda, T., Mase, H., Tom, T., & Oku, Y. (2010). Projection of extreme wave climate change under global warming. *Hydrological Research Letters*, *4*, 15–19. doi:10.3178/hrl.4.15

Mote, P., Brekke, L., Duffy, P. B., & Maurer, E. (2011). Guidelines for constructing climate scenarios. *Eos, Transactions, American Geophysical Union*, *92*(31), 257–258. doi:10.1029/2011EO310001

Munday, P. L., Dixson, D. L., Donelson, J. M., Jones, G. P., Pratchett, M. S., Devitsina, G. V., & Døving, K. B. (2009). Ocean acidification impairs olfactory discrimination and homing ability of a marine fish. *Proceedings of the National Academy of Sciences*, *106*(6), 1848–1852. doi:10.1073/pnas.0809996106

Nakada, M. (1986). Holocene sea levels in oceanic islands: Implications for the rheological structure of the earth's mantle. *Tectonophysics*, *121*(2–4), 263–276. doi:10.1016/0040-1951(86)90047-8

Nerem, R. S., Chambers, D. P., Choe, C., & Mitchum, G. T. (2010). Estimating mean sea level change from the TOPEX and Jason altimeter missions. *Marine Geodesy*, *33*(Suppl 1), 435–446. doi:10.1080/01490419.2010.491031

New Day Hawaiʻi. (2010). A new day in Hawaiʻi: A comprehensive plan. Retrieved from http://newdayhawaii.org/pdf/ANewDayinHawaii.pdf

Nicholls, N. (1988). El Niño–Southern Oscillation and rainfall variability. *Journal of Climate*, *1*(4), 418–421. doi:10.1175/1520-0442(1988)001<0418:ENOARV>2.0.CO;2

NOAA NCDC. (2011, November 3). Global climate change indicators. Retrieved February 19, 2012, from http://www.ncdc.noaa.gov/indicators/

NOAA Pacific Storms Climatology Products. (n.d.). Regional climatology overview—North Pacific. Retrieved February 19, 2012, from http://www.pacificstormsclimatology.org/index.php?page=regional-overview/

Norton, C. W., Chu, P.-S., & Schroeder, T. A. (2011). Projecting changes in future heavy rainfall events for Oahu, Hawaii: A statistical downscaling approach. *Journal of Geophysical Research*, *116*, D17110. doi:10.1029/2011JD015641

Nullet, D., & Giambelluca, T. W. (1990). Winter evaporation on a mountain slope, Hawaii. *Journal of Hydrology*, *112*(3–4), 257–265. doi:10.1016/0022-1694(90)90018-S

Nunn, P. D. (1988). *Vatulele: A study in the geomorphological development of a Fiji Island* (Mineral Resources Department Memoir 2). Ministry of Lands and Mineral Resources.

Nunn, P. D. (2000). Significance of emerged Holocene corals around Ovalau and Moturiki islands, Fiji, southwest Pacific. *Marine Geology*, *163*(1-4), 345–351. doi:10.1016/S0025-3227(99)00114-0

Oki, D. S. (1999). *Geohydrology and numerical simulation of the ground-water flow system of Kona, Island of Hawaii* (US Geological Survey Water-Resources Investigations Report No. 99-4073). Retrieved from http://pubs.er.usgs.gov/publication/wri994073

Oki, D. S. (2004). *Trends in streamflow characteristics at long-term gaging stations, Hawaii* (US Geological Survey Scientific Investigations Report No. 2004-5080). Retrieved from http://pubs.usgs.gov/sir/2004/5080/

Oki, D. S., & Meyer, W. (2001). *Analytical versus numerical estimates of water-level declines caused by pumping, and a case study of the Iao aquifer, Maui, Hawaii* (US Geological Survey Water-Resources Investigations Report No. 00-4244). Retrieved from http://pubs.usgs.gov/wri/wri00-4244/

Oki, D. S., Wolff, R. H., & Perreault, J. A. (2010). *Effects of surface-water diversion on streamflow, recharge, physical habitat, and temperature, Nā Wai ʻEhā, Maui, Hawaiʻi* (US Geological Survey Scientific Investigations Report No. 2010-5011).

PaCIS Research and Assessment Working Group. (2008). *Proposed PaCIS projects*. Report of Working Group 3 break-out session presented at the PaCIS Meeting of Steering Committee and Working Groups, Honolulu, HI. Retrieved from http://research.eastwestcenter.org/ideacenter/PaCIS/PaCIS%20Steering%20Committee%20&%20Working%20groups%20August%202008/PaCIS%20Presentations/PaCIS%20WG3%20project%20ideas.doc

Pandolfi, J. M., Jackson, J. B. C., Baron, N., Bradbury, R. H., Guzman, H. M., Hughes, T. P., Kappel, C. V., et al. (2005). Are U.S. coral reefs on the slippery slope to slime? *Science*, *307*(5716), 1725–1726. doi:10.1126/science.1104258

PEAC Center (Pacific ENSO Applications Climate Center). (2010). American Samoa seasonal rainfall variations during ENSO. Retrieved from http://www.prh.noaa.gov/peac/rain/am_samoa.php

Péquignet, A.-C., Becker, J. M., Merrifield, M. A., & Boc, S. J. (2011). The dissipation of wind wave energy across a fringing reef at Ipan, Guam. *Coral Reefs*, *30*(S1), 71–82. doi:10.1007/s00338-011-0719-5

Petersen, G. (2009). *Traditional Micronesian societies: Adaptation, integration, and political organization*. Honolulu, HI: University of Hawaii Press.

Pirazzoli, P. A., & Montaggioni, L. F. (1988). Holocene sea-level changes in French Polynesia. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *68*(2-4), 153–175. doi:10.1016/0031-0182(88)90037-5

Pfeffer, W. T., Harper, J. T., & O'Neel, S. (2008). Kinematic constraints on glacier contributions to 21st-century sea-level rise. *Science*, *321*(5894), 1340–1343. doi:10.1126/science.1159099

Pirazzoli, P. A., & Montaggioni, L. F. (1986). Late Holocene sea-level changes in the northwest Tuamotu islands, French Polynesia. *Quaternary Research*, *25*(3), 350–368. doi:10.1016/0033-5894(86)90006-2

Polovina, J. J., Dunne, J. P., Woodworth, P. A., & Howell, E. A. (2011). Projected expansion of the subtropical biome and contraction of the temperate and equatorial upwelling biomes in the North Pacific under global warming. *ICES Journal of Marine Science*, *68*(6), 986–995. doi:10.1093/icesjms/fsq198

Polovina, J. J., Howell, E. A., & Abecassis, M. (2008). Ocean's least productive waters are expanding. *Geophysical Research Letters*, *35*, L03618. doi:10.1029/2007GL031745

Power, S. B., & Kociuba, G. (2011). What caused the observed twentieth-century weakening of the Walker Circulation? *Journal of Climate*, *24*(24), 6501–6514. doi:10.1175/2011JCLI4101.1

Pratchett, M. S., Munday, P. L., Graham, N. A. J., Kronen, M., Pinca, S., Friedman, K., Brewer, T. D., et al. (2011). Vulnerability of coastal fisheries in the tropical Pacific to climate change. In J. D. Bell, J. E. Johnson, & A. J. Hobday (Eds.), *Vulnerability of tropical Pacific fisheries and aquaculture to climate change* (pp. 493–576). Noumea, New Caledonia: Secretariat of the Pacific Community.

Pratt, L. W., & Gon, S. M. (1998). Terrestrial ecosystems. In S. P. Juvik & J. O. Juvik (Eds.), *Atlas of Hawaii* (3rd ed., pp. 121–129). Honolulu, HI: University of Hawaii Press.

Pratt, T. K. (2009). Origins and evolution. In T. K. Pratt, C. T. Atkinson, P. C. Banko, J. D. Jacobi, & B. L. Woodworth (Eds.), *Conservation biology of Hawaiian forest birds: Implications for island avifauna* (pp. 3–24). New Haven, CT: Yale University Press.

Presley, T. K. (2005). *Effects of the 1998 drought on the freshwater lens in the Laura Area, Majuro Atoll, Republic of the Marshall Islands* (US Geological Survey Scientific Investigations Report No. 2005-5098). Retrieved from http://pubs.usgs.gov/sir/2005/5098/

Price, J., Giambelluca, T. W., Jacobi, J., Elison Timm, O., Diaz, H. F., & Mehrhoff, L. (2009). *Modeling Hawaiian plant species ranges relative to global climate change*. Poster presented at the Hawaii Conservation Conference, Honolulu, HI.

Rahmstorf, S. (2007). A semi-empirical approach to projecting future sea-level rise. *Science*, *315*(5810), 368–370. doi:10.1126/science.1135456

Rainbird, P. (2004). *The archaeology of Micronesia*. Cambridge, UK, and New York, NY: Cambridge University Press.

Rayner, N. A., Parker, D. E., Horton, E. B., Folland, C. K., Alexander, L. V., Rowell, D. P., Kent, E. C., et al. (2003). Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. *Journal of Geophysical Research*, *108*, 4407. doi:200310.1029/2002JD002670

Richmond, R. H., & Wolanski, E. (2011). Coral reefs: Past efforts and future horizons. In Z. Dubinsky & N. Stambler (Eds.), *Corals reefs: An ecosystem in transition* (pp. 3–12). Dordrecht, The Netherlands: Springer.

Riva, R. E. M., Bamber, J. L., Lavallée, D. A., & Wouters, B. (2010). Sea-level fingerprint of continental water and ice mass change from GRACE. *Geophysical Research Letters*, *37*, L19605. doi:10.1029/2010GL044770

Ropelewski, C. F., & Halpert, M. S. (1987). Global and regional scale precipitation patterns associated with the El Niño/Southern Oscillation. *Monthly Weather Review*, *115*(8), 1606–1626. doi:10.1175/1520-0493(1987)115<1606:GARSPP>2.0.CO;2

Ruggiero, P., Komar, P. D., & Allan, J. C. (2010). Increasing wave heights and extreme value projections: The wave climate of the U.S. Pacific Northwest. *Coastal Engineering*, *57*(5), 539–552. doi:10.1016/j.coastaleng.2009.12.005

Sadler, J. P. (1999). Biodiversity on oceanic islands: A palaeoecological assessment. *Journal of Biogeography*, *26*(1), 75–87. doi:10.1046/j.1365-2699.1999.00285.x

Sagapolutele, F. (2011, June 22). Governor's executive order establishes advisory group to confront climate change. *Samoa News*. Pago Pago. Retrieved from http://208.109.238.104/viewstory.php?storyid=27615&edition=1308733200

Sasaki, W., & Toshiyuki, H. (2007). Interannual variability and predictability of summertime significant wave heights in the western North Pacific. *Journal of Oceanography*, *63*(2), 203–213. doi:10.1007/s10872-007-0022-9

Semedo, A., Bengston, L., Günther, H., Weisse, R., Beherens, A., & Sterl, A. (2012). Impact of a warmer climate on the global wave field. Manuscript submitted for publication.

Seneviratne, S. I., Nicholls, N., Easterling, D., Goodess, C. M., Kanae, S., Kossin, J., Luo, Y., et al. (2012). Changes in climate extremes and their impacts on the natural physical environment. In C. B. Field, V. Barros, T. F. Stocker, D. Qin, D. J. Dokken, K. L. Ebi, M. D. Mastrandrea, et al. (Eds.), *Managing the risks of extreme events and disasters to advance climate change adaptation*, A special report of Working Groups I and II of the Intergovernmental Panel on Climate Change (pp. 109–230). Cambridge, UK, and New York, NY: Cambridge University Press.

Sheppard, C. R. C. (2003). Predicted recurrences of mass coral mortality in the Indian Ocean. *Nature*, *425*(6955), 294–297. doi:10.1038/nature01987

Short, F. T., & Neckles, H. A. (1999). The effects of global climate change on seagrasses. *Aquatic Botany*, *63*(3–4), 169–196. doi:10.1016/S0304-3770(98)00117-X

Sivakumar, M. V. K., & Hansen, J. (Eds.). (2007). *Climate prediction and agriculture: Advances and challenges*. Berlin, Germany: Springer.

Slangen, A. B. A., Katsman, C. A., Wal, R. S. W., Vermeersen, L. L. A., & Riva, R. E. M. (2011). Towards regional projections of twenty-first century sea-level change based on IPCC SRES scenarios. *Climate Dynamics*, *38*(5-6), 1191–1209. doi:10.1007/s00382-011-1057-6

Smith, T. M., & Reynolds, R. W. (2004). Improved extended reconstruction of SST (1854–1997). *Journal of Climate*, *17*(12), 2466–2477. doi:10.1175/1520-0442(2004)017<2466:IEROS>2.0.CO;2

Smith, T. M., Reynolds, R. W., Peterson, T. C., & Lawrimore, J. (2008). Improvements to NOAA's historical merged land–ocean surface temperature analysis (1880–2006). *Journal of Climate*, *21*(10), 2283–2296. doi:10.1175/2007JCLI2100.1

Sohn, B. J., & Park, S.-C. (2010). Strengthened tropical circulations in past three decades inferred from water vapor transport. *Journal of Geophysical Research*, *115*, D15112. doi:10.1029/2009JD013713

Stammer, D., Cazenave, A., Ponte, R. M., & Tamisiea, M. E. (In press). Contemporary regional sea level changes. *Annual Review of Marine Science*, *5*(1). doi:10.1146/annurev-marine-121211-172406

Storlazzi, C. D., Brown, E. K., Field, M. E., Rodgers, K., & Jokiel, P. L. (2005). A model for wave control on coral breakage and species distribution in the Hawaiian Islands. *Coral Reefs*, *24*(1), 43–55. doi:10.1007/s00338-004-0430-x

Storlazzi, C. D., Elias, E., Field, M. E., & Presto, M. K. (2011). Numerical modeling of the impact of sea-level rise on fringing coral reef hydrodynamics and sediment transport. *Coral Reefs*, *30*(Suppl 1), 83–96. doi:10.1007/s00338-011-0723-9

Storlazzi, C. D., Logan, J. B., & Field, M. E. (2003). Quantitative morphology of a fringing reef tract from high-resolution laser bathymetry: Southern Molokai, Hawaii. *Geological Society of America Bulletin*, *115*(11), 1344–1355. doi:10.1130/B25200.1

Strong, A. E., Barrientos, C. S., Duda, C., & Saper, J. (1997). Improved satellite techniques for monitoring coral reef bleaching. In H. A. Lessios & I. G. Macintyre (Eds.), *Proceedings of the 8th International Coral Reef Symposium, 1996 June 24-29* (Vol. 2, pp. 1495–1498). Panama City, Panama: Smithsonian Tropical Research Institute.

Sweet, W. V., Zervas, C., & Gill, S. (2011). *Seasonal variability of storm surge and high water events within the Hawaiian Islands*. Poster presented at the 12th International Workshop on Wave Hindcasting and Forecasting & 3rd Coastal Hazards Symposium, 2011 October 30–November 4, Kohala Coast, Hawai'i.

Swim, J., Clayton, S., Doherty, T., Gifford, R., Howard, G., Reser, J., Stern, P., et al. (2010). *Psychology and global climate change: Addressing a multi-faceted phenomenon and set of challenges. Report of the American Psychological Association Task Force on the interface between psychology and global climate change*. Retrieved from http://www.apa.org/science/about/publications/climate-change.aspx

Takahashi, M., Elison Timm, O., Giambelluca, T. W., Diaz, H. F., & Frazier, A. G. (2011). *High and low rainfall events in Hawai'i in relation to large-scale climate anomalies in the Pacific: Diagnostics and future projections (Abstract #GC51D–1024)*. Poster presented at the American Geophysical Union Fall Meeting, San Francisco, CA.

Takasaki, K. J., & Mink, J. F. (1985). *Evaluation of major dike-impounded ground-water reservoirs, Island of Oahu* (US Geological Survey Water-Supply Paper No. 2217). Retrieved from http://pubs.er.usgs.gov/publication/wsp2217

Teddy, L., Nikora, L. W., & Guerin, B. (2008). Place attachment of Ngāi Te Ahi to Hairini Marae. *MAI Review*, 1. Retrieved from http://researchcommons.waikato.ac.nz/handle/10289/1233

Tegart, W. J. M., Sheldon, G. W., & Griffiths, D. C. (Eds.). (1990). *Climate change: The IPCC Impacts Assessment. Report prepared for Intergovernmental Panel on Climate Change by Working Group II*. Canberra, Australia: Australian Government Publishing Service. Retrieved from http://www.ipcc.ch/publications_and_data/publications_ipcc_first_assessment_1990_wg2.shtml#.T7CUHb_fit8

Timmermann, A., McGregor, S., & Jin, F.-F. (2010). Wind effects on past and future regional sea level trends in the southern Indo-Pacific. *Journal of Climate*, *23*(16), 4429–4437. doi:10.1175/2010JCLI3519.1

Tokinaga, H., Xie, S.-P., Timmermann, A., McGregor, S., Ogata, T., Kubota, H., & Okumura, Y. M. (2012). Regional patterns of tropical Indo-Pacific climate change: Evidence of the Walker Circulation weakening. *Journal of Climate*, *25*(5), 1689–1710. doi:10.1175/JCLI-D-11-00263.1

Townscape, Inc. (2009). *Wai'anae Watershed Management Plan* (Prepared for the Honolulu Board of Water Supply). Honolulu, HI. Retrieved from http://www.boardofwatersupply.com/cssweb/display.cfm?sid=1614

Trenberth, K. E. (1991). General characteristics of El Niño-Southern Oscillation. In M. H. Glantz, R. W. Katz, & N. Nicholls (Eds.), *Teleconnections Linking Worldwide Climate Anomalies* (pp. 13-42). Cambridge, UK: Cambridge University Press.

Trenberth, K. E. (2008). Observational needs for climate prediction and adaptation. *WMO Bulletin*, *57*(1), 17–21.

Turgeon, D. D., Asch, R. D., Causey, B. D., Dodge, R. E., Jaap, W., Banks, K., Delaney, J., et al. (2002). *The state of coral reef ecosystems of the United States and Pacific Freely Associated States: 2002*. Silver Springs, MD: National Oceanic and Atmospheric Administration/National Ocean Service/National Centers for Coastal Ocean Science. Retrieved from http://ccma.nos.noaa.gov/ecosystems/coralreef/coral2002/

United Nations Office for the Coordination of Humanitarian Affairs. (1998). *FSM El Niño Drought OCHA Situation* (Report No. 1). Retrieved from http://reliefweb.int/node/36651

University of Hawai'i at Mānoa (2011). ALOHA Cabled Observatory. Retrieved from http://aco-ssds.soest.hawaii.edu/

Van Nguyen, H., Chen, Y.-L., & Fujioka, F. (2010). Numerical simulations of island effects on airflow and weather during the summer over the island of Oahu. *Monthly Weather Review*, *138*(6), 2253–2280. doi:10.1175/2009MWR3203.1

Varga, T. A., & Asner, G. P. (2008). Hyperspectral and LiDAR remote sensing of fire fuels in Hawaii Volcanoes National Park. *Ecological applications*, *18*(3), 613–623. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/18488621

Vecchi, G. A., Clement, A., & Soden, B. J. (2008). Examining the tropical Pacific's response to global warming. *Eos, Transactions, American Geophysical Union*, *89*(9), 91–83. doi:200810.1029/2008EO090002

Vecchi, G. A., & Soden, B. J. (2007). Global warming and the weakening of the tropical circulation. *Journal of Climate*, *20*(17), 4316–4340. doi:10.1175/JCLI4258.1

Vecchi, G. A., Soden, B. J., Wittenberg, A. T., Held, I. M., Leetmaa, A., & Harrison, M. J. (2006). Weakening of tropical Pacific atmospheric circulation due to anthropogenic forcing. *Nature*, *441*(7089), 73–76. doi:10.1038/nature04744

Vermeer, M., & Rahmstorf, S. (2009). Global sea level linked to global temperature. *Proceedings of the National Academy of Sciences*, *106*(51), 21527–21532. doi:10.1073/pnas.0907765106

Veron, J. E. N., Hoegh-Guldberg, O., Lenton, T. M., Lough, J. M., Obura, D. O., Pearce-Kelly, P., Sheppard, C. R. C., et al. (2009). The coral reef crisis: The critical importance of <350 ppm CO2. *Marine Pollution Bulletin*, *58*(10), 1428–1436. doi:10.1016/j.marpolbul.2009.09.009

Vetter, O., Becker, J. M., Merrifield, M. A., Pequignet, A.-C., Aucan, J., Boc, S. J., & Pollock, C. E. (2010). Wave setup over a Pacific Island fringing reef. *Journal of Geophysical Research*, *115*, C12066. doi:10.1029/2010JC006455

Vitousek, P. M., Ladefoged, T. N., Kirch, P. V., Hartshorn, A. S., Graves, M. W., Hotchkiss, S. C., Tuljapurkar, S., et al. (2004). Soils, agriculture, and society in precontact Hawai'i. *Science*, *304*(5677), 1665–1669. doi:10.1126/science.1099619

Wagner, W. L., Herbst, D. R., & Sohmer, S. H. (1990). *Manual of flowering plants of Hawaii* (Vol. 1). Honolulu, HI: University of Hawaii Press & Bishop Museum Press.

Waikīkī Improvement Association. (2008). *Economic impact analysis of the potential erosion of Waikīkī Beach*. Honolulu, HI. Retrieved from http://www.waikikiimprovement.com/UPLOADS/BeachProject.pdf

Walker, I. J., & Barrie, J. V. (2006). Geomorphology and sea-level rise on one of Canada's most sensitive coasts: Northeast Graham Island, British Columbia. *Journal of Coastal Research*, (Special Issue 39), 220–226.

Wallsgrove, R., & Penn, D. (2012). *Water resources and climate change adaptation in Hawai'i: Adaptive tools in the current law and policy framework*. Honolulu, HI: Center for Island Climate Adaptation and Policy. Retrieved from http://icap.seagrant.soest.hawaii.edu/icap-publications & http://www.islandclimate.org

Wang, X. L., & Swail, V. R. (2006). Climate change signal and uncertainty in projections of ocean wave heights. *Climate Dynamics*, *26*(2), 109–126. doi:10.1007/s00382-005-0080-x

Wannier, G. (2011). Threatened island nations: Summary of legal issues. *Climate Law Blog*. Columbia Law School, Center for Climate Change Law. Retrieved from http://blogs.law.columbia.edu/climatechange/2011/07/11/threatened-island-nations-summary-of-legal-issues/

Waycott, M., McKenzie, L. J., Mellors, J. E., Ellison, J. C., Sheaves, M. T., Collier, C., Schwarz, A.-M., et al. (2011). Vulnerability of mangroves, seagrasses and intertidal flats in the tropical Pacific to climate change. In J. D. Bell, J. E. Johnson, & A. J. Hobday (Eds.), *Vulnerability of tropical Pacific fisheries and aquaculture to climate change* (pp. 297–368). Noumea, New Caledonia: Secretariat of the Pacific Community.

Weart, S. R. (1997). Global warming, cold war, and the evolution of research plans. *Historical Studies in the Physical and Biological Sciences*, *27*(2), 319–356.

Webb, A. P., & Kench, P. S. (2010). The dynamic response of reef islands to sea-level rise: Evidence from multi-decadal analysis of island change in the Central Pacific. *Global and Planetary Change*, *72*(3), 234–246. doi:10.1016/j.gloplacha.2010.05.003

Webster, N., & Hill, R. (2007). Vulnerability of marine microbes on the Great Barrier Reef to climate change. In J. E. Johnson & P. A. Marshall (Eds.), *Climate change and the Great Barrier Reef: A vulnerability assessment* (pp. 97–120). Townsville, Australia: Great Barrier Reef Marine Park Authority. Retrieved from http://www.gbrmpa.gov.au/__data/assets/pdf_file/0003/22593/chapter05-marine-microbes.pdf

Westervelt, W. D. (1910). *Legends of Maui—a demi god of Polynesia, and of his mother Hina.* Honolulu: Hawaiian Gazette.

Wilkinson, C. (2008). *Status of coral reefs of the world: 2008*. Townsville, Australia: Global Coral Reef Monitoring Network & Reef and Rainforest Research Centre. Retrieved from http://www.gcrmn.org/status2008.aspx

Wilson Okamoto Corporation. (2008). *Hawai'i water plan: Water resource protection plan*. Honolulu, HI: State of Hawai'i, Department of Land and Natural Resources, Commission on Water Resource Management. Retrieved from http://hawaii.gov/dlnr/cwrm/planning_wrpp.htm

Wolanski, E., & De'ath, G. (2005). Predicting the impact of present and future human land-use on the Great Barrier Reef. *Estuarine, Coastal and Shelf Science*, *64*(2–3), 504–508. doi:10.1016/j.ecss.2005.03.017

Wolanski, E., Richmond, R. H., & McCook, L. (2004). A model of the effects of land-based, human activities on the health of coral reefs in the Great Barrier Reef and in Fouha Bay, Guam, Micronesia. *Journal of Marine Systems*, *46*(1–4), 133–144. doi:10.1016/j.jmarsys.2003.11.018

Wongbusarakum, S. (2010). *Training summary report: Socioeconomic assessment for Pacific adaptation to climate change (SEA-PACC)* (Training Workshop for Food Security Country Teams). Koror, Palau: Pacific Adaptation to Climate Change Project.

Woodroffe, C. D., & McLean, R. F. (1998). Pleistocene morphology and Holocene emergence of Christmas (Kiritimati) Island, Pacific Ocean. *Coral Reefs*, *17*(3), 235–248. doi:10.1007/s003380050124

Woodroffe, C. D., Stoddart, D. R., Spencer, T., Scoffin, T. P., & Tudhope, A. W. (1990). Holocene emergence in the Cook Islands, South Pacific. *Coral Reefs*, *9*(1), 31–39. doi:10.1007/BF00686719

Woodworth, P. L., Atkinson, C. T., LaPointe, D. A., Hart, P. J., Spiegel, C. S., Tweed, E. J., Henneman, C., et al. (2005). Host population persistence in the face of introduced vector-borne diseases: Hawaii Amakihi and avian malaria. *Proceedings of the National Academy of Sciences*, *102*(5), 1531–1536. doi:10.1073/pnas.0409454102

Woodworth, P. L., & Blackman, D. L. (2004). Evidence for systematic changes in extreme high waters since the mid-1970s. *Journal of Climate*, *17*(6), 1190–1197. doi:10.1175/1520-0442(2004)017<1190:EFSCIE>2.0.CO;2

Woodworth, P. L., Menéndez, M., & Roland Gehrels, W. (2011). Evidence for century-timescale acceleration in mean sea levels and for recent changes in extreme sea levels. *Surveys in Geophysics*, *32*(4-5), 603–618. doi:10.1007/s10712-011-9112-8

Wöppelmann, G., Martin Miguez, B., Bouin, M.-N., & Altamimi, Z. (2007). Geocentric sea-level trend estimates from GPS analyses at relevant tide gauges world-wide. *Global and Planetary Change*, *57*(3–4), 396–406. doi:10.1016/j.gloplacha.2007.02.002

The World factbook. (2011). Washington, DC: Central Intelligence Agency. Retrieved from https://www.cia.gov/library/publications/the-world-factbook/geos/gq.html

World Health Organization. (2010). *Climate change and health* (Fact Sheet No. 266). Retrieved from http://www.who.int/mediacentre/factsheets/fs266/en/

Wyant, M. C., Wood, R., Bretherton, C. S., Mechoso, C. R., Bacmeister, J., Balmaseda, M. A., Barrett, B., et al. (2010). The PreVOCA experiment: Modeling the lower troposphere in the Southeast Pacific. *Atmospheric Chemistry and Physics*, *10*(10), 4757–4774. doi:10.5194/acp-10-4757-2010

Wyrtki, K. (1975). El Niño: The dynamic response of the equatorial Pacific Ocean to atmospheric forcing. *Journal of Physical Oceanography*, *5*(4), 572–584. doi:10.1175/1520-0485(1975)005<0572:ENTDRO>2.0.CO;2

Xie, S.-P., Deser, C., Vecchi, G. A., Ma, J., Teng, H., & Wittenberg, A. T. (2010). Global warming pattern formation: Sea surface temperature and rainfall. *Journal of Climate*, *23*(4), 966–986. doi:10.1175/2009JCLI3329.1

Yamaguchi, K., & Noda, A. (2006). Global warming patterns over the North Pacific: ENSO versus AO. *Journal of the Meteorological Society of Japan. Ser. II*, *84*(1), 221–241. doi:http://dx.doi.org/10.2151/jmsj.84.221

Young, I. R., Zieger, S., & Babanin, A. V. (2011). Global trends in wind speed and wave height. *Science*. doi:10.1126/science.1197219

Young, W. J. (2007). *Climate risk profile for Samoa*. Samoa Meteorology Division. Retrieved from http://www.mnre.gov.ws/documents/projects/climate/SNC/Samoa%20CRP%20Updated%20ver%202007%20Final.pdf

Yu, B., & Zwiers, F. W. (2010). Changes in equatorial atmospheric zonal circulations in recent decades. *Geophysical Research Letters*, *37*, L05701. doi:10.1029/2009GL042071

Yu, J., Wang, Y., & Hamilton, K. (2010). Response of tropical cyclone potential intensity to a global warming scenario in the IPCC AR4 CGCMs. *Journal of Climate*, *23*(6), 1354–1373. doi:10.1175/2009JCLI2843.1

Yu, L., & Weller, R. A. (2007). Objectively analyzed air–sea heat fluxes for the global ice-free oceans (1981–2005). *Bulletin of the American Meteorological Society*, *88*(4), 527–539. doi:10.1175/BAMS-88-4-527

Zhang, C., Wang, Y., & Hamilton, K. (2011). Improved representation of boundary layer clouds over the southeast Pacific in ARW-WRF using a modified Tiedtke cumulus parameterization scheme. *Monthly Weather Review*, *139*(11), 3489–3513. doi:10.1175/MWR-D-10-05091.1

Zhang, C., Wang, Y., Lauer, A., & Hamilton, K. (2012). Configuration and evaluation of the WRF model for the study of Hawaiian regional climate. *Monthly Weather Review*, 120502071935003. doi:10.1175/MWR-D-11-00260.1

Zhang, Y., Chen, Y.-L., Hong, S.-Y., Juang, H.-M. H., & Kodama, K. (2005a). Validation of the coupled NCEP mesoscale spectral model and an advanced land surface model over the Hawaiian Islands. Part I: Summer trade wind conditions and a heavy rainfall event. *Weather and Forecasting*, *20*(6), 847–872. doi:10.1175/WAF891.1

Zhang, Y., Chen, Y.-L., & Kodama, K. (2005b). Validation of the coupled NCEP mesoscale spectral model and an advanced land surface model over the Hawaiian Islands. Part II: A high wind event. *Weather and Forecasting*, *20*(6), 873–895. doi:10.1175/WAF892.1

Ziegler, A. C. (2002). *Hawaiian natural history, ecology, and evolution*. Honolulu, HI: University of Hawaii Press.

Climate Change and Pacific Islands: Indicators and Impacts is being published as one of a series of technical inputs to the National Climate Assessment (NCA) 2013 report. Developed by the Pacific Islands Regional Climate Assessment (PIRCA), this report assesses the state of knowledge about climate change indicators, impacts, and adaptive capacity of the Hawaiian archipelago and the US-Affiliated Pacific Islands (USAPI). The PIRCA is a collaborative effort engaging federal, state, and local government agencies, non-government organizations, academia, businesses, and community groups to inform and prioritize their activities in the face of a changing climate.

Cover photos: (*Top*) View from Makapuʻu Point on the island of Oʻahu in Hawaiʻi, courtesy of Zena N. Grecni. (*Middle Left*) Tropical Pacific coral reef, Palmyra Atoll National Wildlife Refuge, courtesy of J. Maragos. (*Middle Right*) Pacific fish hook collection, Bishop Museum, Honolulu, Hawaiʻi, © 2008 Debbie Long, "hooked", used under a Creative Commons Attribution-NonCommercial-ShareAlike license. (*Bottom*) Clouds around Mount Konahuanui in the Koʻolau Mountain Range, Oʻahu, courtesy of Zena N. Grecni.

Cover design: Maureen Gately

ISBN 13: 978-1-61091-427-7
ISBN 10: 1-61091-427-9
90000 >
9 781610 914277

ISLANDPRESS

Washington | Covelo | London
www.islandpress.org
All Island Press books are printed on recycled, acid-free paper.