2024

Philippine Climate Change Assessment

WORKING GROUP 1

The Physical Science Basis

Oscar M. Lopez Center
Science for Climate Resilient Communities

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2024

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Dr. Basconcillo holds a PhD in Marine Meteorology from Jeju National University and a MS in Meteorology from the UP Diliman. He has been a Weather Specialist for DOST-PAGASA since 2013. Prior to this, he had various research and information system experience, which included being a researcher at the Typhoon Research Center in Jeju City, South Korea. Dr. Basconcillo has extensive research on climate and atmospheric science in international and Philippine journals. His memberships in professional organizations include being a Section Head in Meteorology & Oceanography, Division of Earth and Space Sciences in the National Research Council of the Philippines, and Vice-President of the Philippine Meteorological Society.

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Dr. John Manalo holds a PhD in Science from the Tokyo Metropolitan University and is a Weather Specialist at DOST-PAGASA. His research activities include understanding the effect of urbanization on temperature indices in the Philippines, Diurnal Variability of Urban Heat Island Intensity, climate variability, climate change, and understanding the influence of various atmospheric systems (i.e., ISO) on rainfall extremes in the Philippines. He is also involved in the development of the CMIP6-based climate projection in the Philippines and dissemination of these climate information in the country.

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Her engagement in the field of climate change includes doing research and projects on climate, climatology, and climate trends, detection, and attribution of observed impacts to climate change and climate change adaptation. She has also served as a referee for international journals on climate/climate change, in addition to being active in the preparation of the Intergovernmental Panel on Climate Change (IPCC) global scientific assessment reports (AR), a Government Reviewer for IPCC AR4, Lead Author of the WG2 contribution to IPCC AR5, and of the IPCC Special Report on Climate Change, Oceans and the Cryosphere. She co-authored three books on climate change in the Philippines, which were awarded the Most Outstanding Book of the Year in 2001, 2015, and 2022 by the National Academy of Science and Technology, Philippines.

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Foreword

Executive Summary

The 2021 Working Group 1 (WG1) contribution to the 6th Assessment Report of the Intergovernmental Panel on Climate Change provided strong evidence of unequivocal human influence on the observed warming in the atmosphere, ocean, and on land, which is already affecting weather and climate extremes in every region. It also described an objective view of the physical conditions of the climate system (e.g., means, events, and extremes) in terms of climatic impact-drivers (CIDs) that can cause positive, negative, or no change in natural and human systems, depending on the tolerance of these systems. The current climate in most regions, including Southeast Asia, is already different from the climate in the early or mid-20th century. The *likely* range of total human-caused global surface temperature increase from 1850–1900 to 2010–2019 is 0.8 °C–1.3 °C, with a best estimate of 1.07 °C. A new set of illustrative emission scenarios referred to as shared socioeconomic pathways (SSPs) indicates the continued rise in global surface temperature, albeit at varying rates. With further global warming, larger changes in climate are projected, including more frequent and more intense hot extremes, a more intense global water cycle, more severe wet and dry events, an increased fraction of intense tropical cyclones (TCs), and an increase in relative sea levels. An increase in the global temperature of 1.5 °C is *likely* to be exceeded at the end of the 21st century unless immediate and deep cuts in carbon dioxide and other greenhouse gas emissions are done before the middle of this century.

In the Philippines, based on records from 1951–1980, the annual mean temperature is observed to be increasing by 0.16 °C per decade. Higher and more significant trends were observed in nighttime temperatures than in the daytime, particularly during December to February. The urbanization effect on temperature trends, quantified from satellite night lights, also showed a larger and more significant effect at night than during the day. For example, the homogenized long-term temperature data in Metro Manila from 1901–2018 indicated a significant increase in the number of warm nights, and decrease in the number of cool nights, a trend that is consistent with countrywide analysis.

Rainfall in the Philippines is influenced by different atmospheric processes, such as wind systems and high-pressure areas, on varying spatial and temporal scales. During the *Habagat* (southwest monsoon) and *Amihan* (northeast monsoon) seasons, for example, rainfall is affected by the Western North Pacific Subtropical High. This high-pressure system has been observed to influence the onset of *Habagat*, monsoon breaks over Luzon, and the tracks of TCs in general. Climate shifts were also observed to arise from phase changes in the Pacific Decadal Oscillation (PDO). Local studies have contributed to our understanding of factors, such as winds, sea surface temperature, topography, land cover, and others, that drive rainfall variability.

The historical record on the annual frequency and intensity of TCs in the Philippines shows no discernible long-term trend, although the number of so-called Christmas typhoons has significantly increased by 210% since 2012. As cited in many TC studies, the reliability of such temporal analysis of TC climatology depends on the quality of best track data, thus making attribution to global warming truly challenging.

Significant increases in TC-induced rainfall in the Philippines have been observed since 2000, ranging from 16.9% to 19.3% per decade. From 1958–2017, there has been a significant increase of 6.0% per decade in the mean annual number of high precipitation event (HPE) days and 12.7% per decade in the annual total HPE precipitation, both of which are primarily due to TCs. Non-TC vortices (i.e., weaker disturbances than TCs), which occur more frequently during the December-January-February season, have a significant contribution to the mean daily rainfall in northeast Mindanao.

Using satellite data from 1993–2015, sea level was estimated to rise 5–7 mm per year over the Philippine Sea and 4.5–5 mm per year in some parts of the country, such as the east of Samar and Leyte, regions along the southwestern coasts of the Central and Western Visayas, and the east of Mindanao and south Zamboanga. This large increase in sea level has been suggested to be partly due to natural modes of ocean variability, such as El Niño Southern Oscillation (ENSO) and PDO, and partly due to anthropogenic factors.

Future climate warming in the Philippines is projected to range from an annual average of 2.5 °C in the RCP 4.5 scenario to 4.1 °C in the RCP 8.5 scenario by the end of the 21st century. During the hotter months of March, April, and May, the mean temperature is projected to increase by 1.3 °C–2.2 °C even earlier, that is, by mid-century. Efforts are now underway to use the new suite of SSPs to update estimation of future climate change in the Philippines.

Future changes in rainfall are much more difficult than temperature to estimate due to the disparities in model output. Some models indicate a wetter future, while others project drier conditions. Future changes (increase or decrease) in average rainfall can reach 40% in certain areas of the country by mid-century.

As a measure of extreme rainfall events, the maximum 1-day rainfall is projected to increase by 20%–25% over western and southern Luzon, southern Visayas, and western and southeastern sections of Mindanao by the end of the century.

On TCs, the prognosis from the current set of downscaled climate simulations suggests a slight decrease in TC occurrence over the Philippine Area of Responsibility, but more intense TCs in a future that is based on the RCP 8.5 scenario. The caveat here is that models continue to be limited, especially when it comes to capturing the climatological characteristics of TCs.

Gaps in observations and modeling projections

Several CIDs are broadly relevant to Southeast Asia, such as drought (meteorological, hydrological, agricultural, and ecological), fire weather, winds, and others. There is *low confidence* in the direction of these observed and projected changes, as well as in the extent of human contribution. Hence, this presents potential directions for research in the region, including the Philippines.

PhilCCA 2016 identified many areas that needed further examination, such as the influence of large-scale climate drivers (e.g., ENSO, Madden–Julian Oscillation, and PDO) on the Philippine climate, the effect of sea level rise on saltwater intrusion and storm surges along coastal areas, local climate impacts of aerosols and land use change, as well as their interaction with the enhanced greenhouse effect. While there have been significant strides made in climate science in the Philippines since that first report, these underexplored areas remain a continuing concern.

There is limited information or literature on observed trends in sea level change over the country and on the variability and trend of other TC metrics (e.g., duration, speed, and others). On the latter, there is a need to identify a reliable TC period to study trends and other characteristics of TCs in the Philippines.

Gaps in observational data need particular and urgent attention. Modeling past, present, and future climate change depends on the quality of the observed data. Despite recent advances in regional climate modeling, in collaboration with partners in the country, Southeast Asia, and the international modeling community, model biases and uncertainties remain and need to be resolved. A robust observational network will certainly increase confidence in estimating future climate change and its impacts in the Philippines.

Finally, the country's climate science community acknowledges a non-research–related gap, which is the limited involvement and collaboration with the various stakeholders and users of climate data and information. The dearth of scientific communication expertise compounds this gap. Greater exchange between science and society will enable the co-creation of responsive climate decisions and policies, the timely execution of these policies, and a safer climate, especially for the more vulnerable.

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The Oscar M. Lopez Center for Climate Change Adaptation and Disaster Risk Management Foundation Inc. would like to extend our deepest gratitude to all who have contributed to the development and publication of the 2024 Philippine Climate Change Assessment Report: *The Physical Science Basis.*

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- Department of Science and Technology -Philippine Atmospheric, Geophysical and Astronomical Services Administration
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Definition of Terms

Boreal Summer Intraseasonal Oscillation (BSISO)

A mode of bimodal tropical intraseasonal oscillation that is pronounced during the tropic's boreal summer. It propagates along the equator toward the north over the northern Indian Ocean and western North Pacific over a 30- to 60-day period. BSISO is the counterpart of the Madden–Julian Oscillation (MJO) that is dominant during boreal winter.

Coupled Model Intercomparison Project Phase (CMIP)

CMIP is a climate modelling activity from the World Climate Research Programme that coordinates and archives climate model simulations based on shared model inputs by modelling groups from around the world. The (CMIP3) multi-model data set includes projections using Special Report on Emissions Scenarios (SRES) scenarios. The CMIP5 data set includes projections using the Representative Concentration Pathways (RCP). The CMIP6 phase involves a suite of common model experiments including an ensemble of CMIP-endorsed Model Intercomparison Projects.

Shearlines

Result from the interaction between the cold northeasterlies and the warm tropical easterlies, enhancing moisture convergence. Warmer air rises due to its lower density than the colder air mass, causing increased ascent, buoyancy difference, and moisture convergence. In the Philippines, the phrase "tail-end of a cold front" is also used to describe the shearlines.

Convective Permitting Model (CPM)

A weather forecasting method suited for representing land surface characteristics and small-scale processes in the atmosphere, such as convection. The use of this method in complex regions, such as the Philippines, may improve simulations of convective processes.

Daily minimum temperature (Tmin)

Represents the minimum value of air temperature within a day.

Daily maximum temperature (Tmax)

Represents the maximum value of air temperature within a day.

Digital Elevation Model (DEM)

A representation of the bare topographic surface of the earth, excluding trees, buildings, and other surface objects. Widely used to assess changes in sea level.

Diurnal temperature range (DTR)

The difference between the minimum and maximum temperature during a day.

El Niño Southern Oscillation (ENSO)

A periodic oscillation related to the changes in sea surface temperature (SST) in the east central Pacific Ocean with three phases: El Niño, La Niña, and Neutral. During the El Niño phase, SST in the central and eastern Pacific is above normal, while the La Niña phase happens when SST is below normal. The Neutral phase happens when the average SST is close to normal.

Emissions scenario

Refers to what is released or given off by a source, such as energy radiation. For example, the burning of fossil fuels results in the release of greenhouse gas emissions into the atmosphere.

Extratropical cyclones

Also known as wave cyclones or midlatitude cyclones, this is a particular category of storm system that develops at medium or high latitudes in frontal zones, which are areas with significant horizontal temperature changes. The more severe cyclones or hurricanes of the tropics, which occur in areas of somewhat consistent temperature, stand in contrast to extratropical cyclones.

General Circulation or Global Climate Model (GCM)

Also referred to as the climate model. A mathematical representation demonstrating climate interactions between its various components. Models are research tools that provide representations of the climate system in a variety of ways, ranging from rather simple to very complex.

Greenhouse Gas (GHG)

Any of a number of naturally occurring or anthropogenic gases in the atmosphere that absorb and emit radiation, effectively causing the greenhouse effects. The primary greenhouse gases in the Earth's atmosphere are water vapor, carbon dioxide, nitrous oxide, methane, and ozone.

Glacial isostatic adjustment (GIA)

The response of the Earth's surface to the movement of the ice-age glaciers. It is also one of the three factors that is hypothesized to contribute to the regional differences in sea level change.

Global warming level (GWL)

The overall response of surface temperature to anthropogenic emissions in unconstrained simulations of Phase 6 of the Coupled Model Intercomparison Project.

Hadley circulation

Also known as the Hadley Cell. It is made up of a single wind system in each hemisphere, with eastward and poleward flow at higher altitudes and westward and equatorward flow close to the surface.

High precipitation event (HPE)

Extreme weather events characterized by heavy rainfall, causing flooding and landslides.

Intertropical Convergence Zone (ITCZ)

An area near the equator where trade winds from the north and south hemispheres converge, resulting in a low-pressure area, strong convection, and precipitation. The ITCZ moves throughout the year.

Land-ocean thermal contrast

The difference in temperature between the surface of the land and the water. Due to differences in heat capacity and thermal conductivity, the land surface heats up and cools down more quickly than the ocean surface. Sea breezes, monsoons, and other weather phenomena can emerge as a result of this temperature disparity.

Madden–Julian Oscillation

A major contributor to intraseasonal atmospheric variability in tropical regions, with a period ranging from approximately 30–90 days. The MJO moves eastward and affects precipitation, especially over the Indian and western Pacific Oceans.

Pacific Decadal Oscillation (PDO)

A pattern of coupled atmosphere–ocean variability in the Pacific Basin occurring at decadal timescales that can be described by sea surface temperature anomalies over the North Pacific. While ENSO cycles typically last only 6–8 months, the PDO can last from 20–30 years. Like the ENSO, the PDO also consists of warm and cool phases.

Pacific Decadal Variability (PDV)

A key component of decadal variability in the climate system, with significant effects on marine ecosystems, fisheries, and global climate, and as a time-varying component of the mean state, influencing higher-frequency climate variability. PDV can be thought of as stochastic atmospheric variability's reddening process in the oceanic background state. It has a variety of ocean–atmosphere modes and is brought on by a number of processes. On decadal timescales, ENSO teleconnections, stochastic atmospheric forcing, and changes in the North Pacific oceanic gyre circulation all contribute roughly equally. The PDO index is reconstructed at interannual time scales as the sum of random and ENSO-induced variability in the Aleutian Low.

Pluvial flood

One of the three common types of flooding that usually occurs when heavy rainfall creates a flood event independent of an overflowing water body. It is also known as surface water floods, and it can happen everywhere, in both urban and rural settings, even when there are no nearby bodies of water. Flooding and surface runoff are brought on by heavy rainfall that exceeds the ability of the ground to absorb it.

Power dissipation index (PDI)

Measures a tropical cyclone's life span total power. It is calculated by adding up the cyclone's life span maximum wind speed cube at 6-hour intervals and dividing by 10^4. Studies on tropical cyclones (TCs) and climate change frequently employ the PDI to calculate the destructive potential of tropical storms. Since the mid-1970s, the PDI has been observed to be rising in the North Atlantic basin, which is consistent with an increase in hurricane severity and frequency there.

Radiative forcing

A quantifiable change in the net radiative flux at the tropopause as a result of the influence of external drivers of climate change, such as an increased concentration of GHGs in the atmosphere.

Regional Climate Model (RCM)

A climate model with high resolution used to dynamically downscale global reanalyses or climate model output over a defined area. It is consistently referred to as the regional climate model system in some references.

Representative Concentration Pathway (RCP)

Scenarios used for climate modeling and research, which takes into account emissions and concentrations of GHGs, aerosols, and chemically active gases, as well as land use and land cover, and plot them against a time series to describe possible climate futures.

Shared socioeconomic pathway (SSP)

Describes five narratives of the future socioeconomic trend into scenarios and shared policy assumptions. Each pathway represents an approximate radiative forcing based on the scenario assumptions up to the year 2100. The SSPs are comprised of sustainable development with low to very low emissions declining to net zero by 2050 or after (SSP1), middle-of-the-road development with intermediate emission (SSP2), regional rivalry with high emission (SSP3), inequality and adaptation challenges dominated (SSP4), and fossil-fueled development leading to very high emissions (SSP5).

Standardized Precipitation Index (SPI)

An index that uses precipitation to represent abnormal wetness or meteorological drought in a range of timescales.

Thermal expansion

The increase in volume and decrease in density of the ocean as a result of higher ocean temperature.

Tropical cyclone (TC)

The general term for a cyclone that forms over the tropical oceans. Cyclones are low pressure systems in which winds spin inward in a circularly symmetric spiral, bringing with them intense rain and winds. Tropical depressions, tropical storms, hurricanes, and typhoons are all forms of TCs.

Urban heat island (UHI) effect

Refers to the replacement of cities' natural land cover, which absorbs and retains heat.

Walker Circulation

Temperature-driven atmospheric circulation described by air rising in the west and falling in the east over the tropical Pacific Ocean.

Weather Research and Forecasting (WRF) model

A mesoscale numerical weather prediction model that is designed for atmospheric research and operational forecasting needs across scales from tens of meters to thousands of 22 kilometers. It has a data assimilation system and a software architecture supporting parallel computation and system extensibility.

List of Abbreviations

ALOS	Advanced Land Observing Satellite
AMO	Atlantic Multidecadal Oscillation
AVISO	Archiving, Validation, and Interpretation of Satellite Oceanographic
BSISO	Boreal Summer Intraseasonal Oscillation
CCKP	Climate Change Knowledge Portal
CDD	Consecutive Dry Days
CDRA	Climate and Disaster Risk Assessment
CID	Climatic Impact-Driver
CMIP	Coupled Model Intercomparison Project
CORDEX	Coordinated Regional Climate Downscaling Experiment
CPM	Convective Permitting Model
DEM	Digital Elevation Model
DJF	December to February
DOST-PAGASA	Department of Science and Technology-Philippine Atmospheric, Geophysical and Astronomical Services Administration
DTR	Diurnal Temperature Range
ENSO	El Niño Southern Oscillation
ETWL	Extreme Total Water Level
GCM	Global Climate Model
GHG	Greenhouse Gas
GIA	Glacial Isostatic Adjustment
GMSL	Global Mean Sea Level
GWL	Global Warming Level
HPE	High Precipitation Event
IOBW	Indian Ocean Basin Wide
IOD	Indian Ocean Dipole
IPCC	Intergovernmental Panel on Climate Change
ISO	Intraseasonal Oscillations
ITCZ	Intertropical Convergence Zone
JJA	June to August
LAS	Less Active Season
LGU	Local Government Unit
LMI	Lifetime Maximum Intensity
MAM	March to May
JTWC	Joint Typhoon Warning Center
LCCAP	Local Climate Change Action Plan
MAS	More Active Season
MHW	Marine Heatwave
MJO	Madden–Julian Oscillation
NOAA	National Oceanic and Atmospheric Administration
PAR	Philippine Area of Responsibility
PDI	Power Dissipation Index
PDO	Pacific Decadal Oscillation
PDV	Pacific Decadal Variability
PhilCCA	Philippine Climate Change Assessment
PMM	Pacific Meridional Mode
RCM	Regional Climate Model
RCP	Representative Concentration Pathway
RSL	Relative Sea Level
RSLR	Relative Sea Level Rise
RSMC	Regional Specialized Meteorological Center
Rx1day	Maximum 1-day rainfall
Rx5day	Maximum 5-day rainfall
SON	September to November
SRES	Special Report Emissions Scenarios
SPEI	Standardized Precipitation Evapotranspiration Index
SPI	Standardized Precipitation Index

SRES	Special Report Emissions Scenarios
SSP	Shared Socioeconomic Pathway
SST	Sea Surface Temperature
TC	Tropical Cyclone
Tmax	Maximum temperature
Tmin	Minimum temperature
TN10p	Percentage of days when Tmin is less than the 10th percentile
TN90p	Percentage of days when Tmin is greater than the 90th percentile
TNn	Minimum value of Tmin
TNx	Maximum value of Tmin
TX10p	Percentage of days when Tmax is less than the 10th percentile
TX90p	Percentage of of days when Tmax is less than the 10th percentile
TXx	Maximum value of Tmax
UHI	Urban Heat Island
WG1	Working Group 1
WNP	Western North Pacific
WNPMI	Western North Pacific Summer Monsoon Index
WNPSH	Western North Pacific Subtropical High
WRF	Weather Research and Forecasting

Introduction

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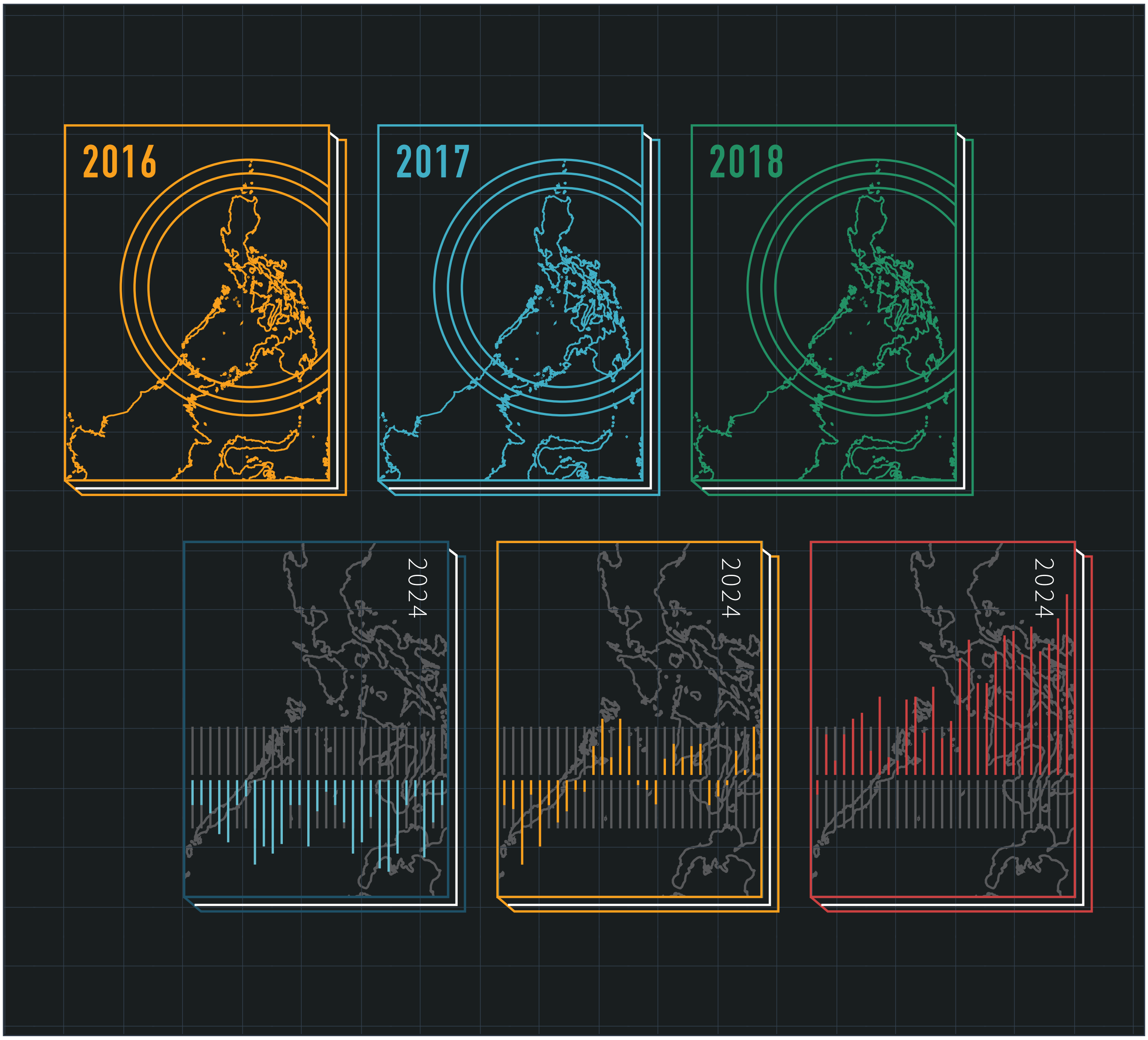

As with the first cycle of the Philippine Climate Change Assessment (PhilCCA) published in 2016 (Villarin *et al.*, 2016), this 2024 report (PhilCCA 2024) is a review and update of scientific research on climate change done in the Philippines. Patterned after the global assessment reports of the Intergovernmental Panel on Climate Change (IPCC), this report by Working Group 1 focuses on the physical science basis of climate change, that is, on understanding the physical mechanisms that drive climate in this part of the world, including the possible local effects that come from increased greenhouse gas (GHG) levels in the atmosphere.

While first PhilCCA reviewed the results of scientific work on the Philippine climate based on local and international research undertaken prior to 2016, PhilCCA 2024 provides an update of the country's climate from scientific work done since 2016. Despite the dearth of local expertise in climate science and in science in general, it is worthwhile to note that there has been a considerable increase in climate science research since 2016. This is evidenced by an increase of about 220%, or a tripling in the number of scientific papers on the Philippine climate that have been published since 2016.

This 2024 Philippine assessment comes after the global Sixth Assessment Report (AR6) by Working Group 1 (Physical Science Basis) of the IPCC that was released in August 2021 (IPCC, 2021). Noteworthy in the AR6 is the contribution of three Filipino climate scientists, namely Drs Gemma Narisma, Faye Cruz, and Laurice Jamero, who worked mainly on the science of regional climate change, i.e., on understanding how changes in global climate will cascade into sub-global or regional scales. Now in use all over the world, the IPCC regional climate atlas in the AR6 has been dedicated to Dr. Narisma.

This report is organized as follows:

Chapter 2 sets the wider global and regional (i.e., Southeast Asia) context within which to situate this Philippine assessment. The chapter is divided into two parts that provide a diagnosis and prognosis of climate change. The first part is about changes and trends in climate that have been observed thus far on both global and regional scales. The second part is about future climate change on these same scales. Each part, where available and appropriate, presents changes in climate variables such as temperature, the water cycle, monsoons and other climate modes of variability, sea level, and climatic impact-drivers, among others.

Chapter 3 is a diagnostic assessment of climate change in the Philippines. It presents changes and trends in key climate variables that have been observed and analyzed from the historical record and various sources of observational data. The four climate variables that are covered here are temperature, rainfall, tropical cyclones (TCs), and sea level. Changes and trends in these variables include climatological totals, means, and extremes wherever available, and the complex role that climate modes of variability such as monsoons and atmosphere–ocean cycles play in driving Philippine climate.

Chapter 4 is about projected changes in the Philippine climate in this century. In PhilCCA 2016, climate prognosis was based on just one regional climate model that was downscaled from one global model for three Special Report on Emission Scenarios (SREs) scenarios representing low-, mid-, and high-range emission pathways (Philippine Atmospheric, Geophysical and Astronomical Services Administration [PAGASA], 2011). Since then, as indicated here in PhilCCA 2024, confidence in Philippine climate projections has increased with the application of multiple dynamically downscaled projections based on intermediate and high emission pathways, i.e., RCP 4.5 and RCP 8.5, respectively (DOST-PAGASA *et al.*, 2021). This chapter presents the methods used in predicting Philippine climate and the results of these simulations, which improve estimates of future changes in temperature, rainfall, and TCs in the country.

Each chapter in this report ends with an assessment of research gaps and recommendations for future research. As mentioned in PhilCCA 2016, one of the more challenging problems in climate science is knowing how a planetary phenomenon such as global climate change will manifest itself on finer spatial and temporal scales, especially in this part of the world that is not as well studied and understood as in other domains. At such local and shorter time scales, climate forcings other than long-term GHG warming come into play. Comparatively short-lived aerosols, urban and rural land morphology, island and ocean dynamics, and other such factors add to the complexity of local climate diagnosis and prognosis. Moreover, the interaction of anthropogenic (or human-caused) warming with other natural climate drivers in the tropics and subtropics makes the Philippine climate complex and challenging. Climate scientists probing the many unknowns in this part of the world have their work cut out for them in the coming years.

In an emerging economy where resources are tight, various unknowns—however interesting—may just need to be left unexplored. Consequently, the need to connect social, ecological, and local questions to scientific ones becomes even more urgent. It is hoped that the Philippine climate science will be sustained and strategically focused, not just for the sake of the country but also for the good of other vulnerable countries similarly situated in the tropics. There is still time to make that happen, to make science matter in the decisions and actions to be carried out for the Philippines to pull through this climate emergency.

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Changes in the Global and Southeast Asia Climate

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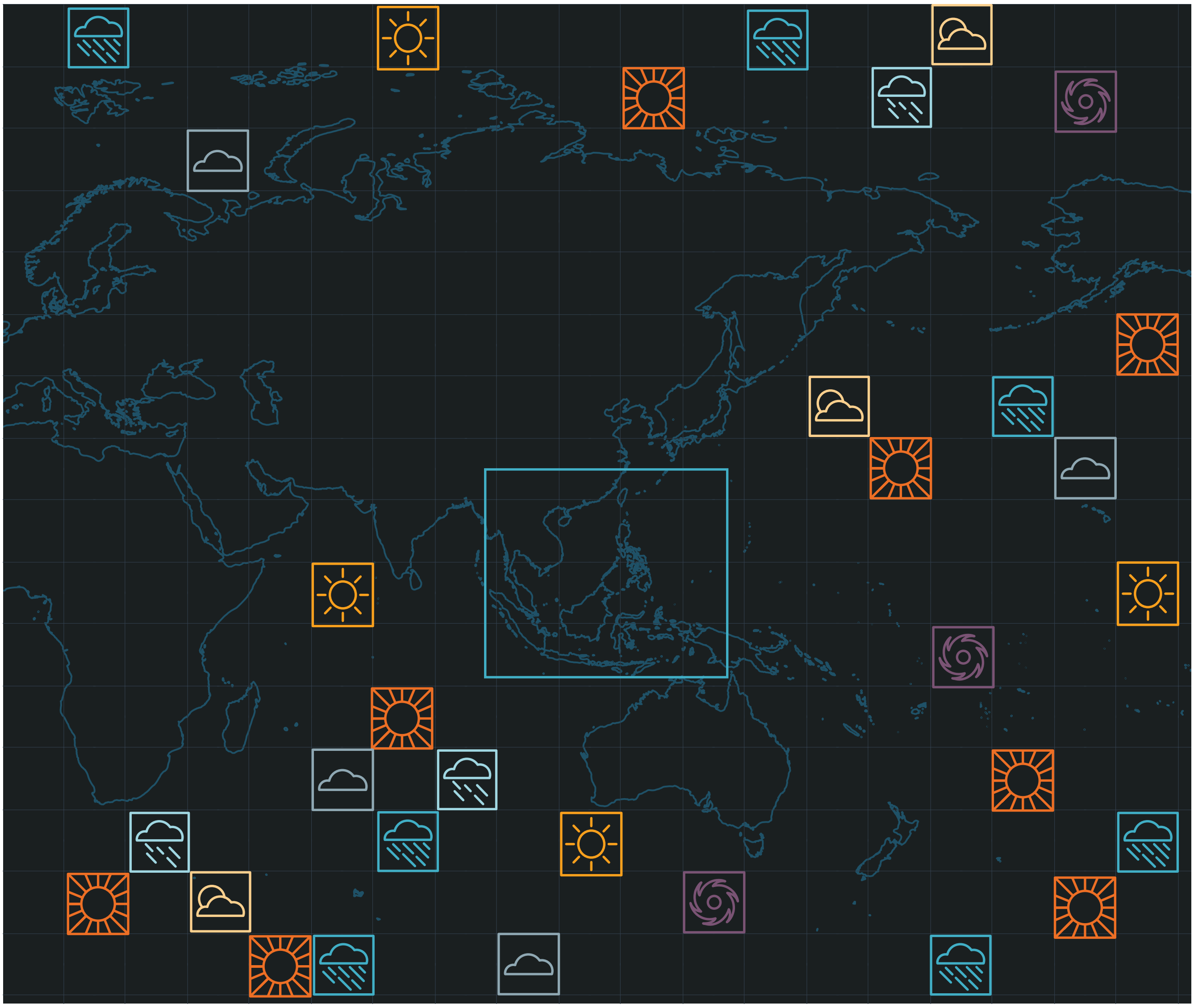

2.1 Chapter Summary

This chapter highlights the recent findings concerning observed and projected changes in climate at the global and regional scales, with a focus on Southeast Asia. It provides an overview and sets the global and regional context for the assessment of observed and projected changes in climate in the Philippines, which will be discussed in subsequent chapters. Information is based mainly on the contribution of Working Group 1 (WG1) to the Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC) on the physical science basis of climate change, particularly the Summary for Policymakers and the Technical Summary. Other more recent scientific literature, particularly those published after the cutoff date for the AR6, is also referred to in this chapter, where relevant.

IPCC AR6 WG1 presents major advances associated with data and documentation (e.g., observations, paleoclimate records, models, and scientific literature) related to the climate system. There is now a clearer perspective on each component of the climate system, including the atmosphere, ocean, cryosphere, and biosphere, and their changes. The scale and rate of these recent changes in the climate system have been unseen in centuries or millennia. More importantly, the report concludes that the human influence on the observed warming in the atmosphere, ocean, and land is unequivocal, and that warming is already affecting weather and climate extremes in every region.

The report also introduced the term "climatic impact-drivers" (CIDs), a more neutral way to refer to conditions of the physical climate as described by means, events, or extremes that would have impacts on society or ecosystems. As such, CIDs and their changes could have positive, negative, neutral, or mixed impacts, depending on the affected system and region. The seven CID types are heat and cold, wet and dry, wind, snow and ice, coastal, open ocean, and other.

As observed in several CIDs, the current climate in most regions is already different from the climate of the early or mid-20th century. There is *high confidence* that climate change has affected CIDs in terms of magnitude, frequency, duration, seasonality, and spatial extent of associated indices. Past changes in some CIDs in some regions have been attributed to human activities. In Southeast Asia, observation records indicate that the intensity and frequency of hot extremes have increased while cold extremes have decreased, which can be attributed to human activities (*high confidence*). Heavy precipitation events have intensified in the region (*medium confidence*), but there is *low confidence* in the observed trends in meteorological, agricultural and ecological, and hydrological droughts due to inconsistent trends between subregions, indices used, and/or limited evidence. Relative sea level (RSL) has also increased in Southeast Asia, but land subsidence resulting from groundwater extraction also needs to be considered as a factor in this increase.

A range of plausible futures, as presented in the IPCC AR6 WG1, is described by a set of illustrative emission scenarios referred to as shared socioeconomic pathways (SSPs). All scenarios indicate a continued increase in global surface temperature until at least the mid-21st century. The report states that rapid and substantial reductions in carbon dioxide and other greenhouse gas (GHG) emissions are necessary to limit global warming below 1.5 °C or 2 °C this century. Many changes in the climate system become larger with further global warming, including more frequent and more intense hot extremes; a more intense global water cycle, including variability, global monsoon precipitation, and more severe wet and dry events; an increased proportion of intense tropical cyclones (TCs); and reductions in snow cover, permafrost, and Arctic Sea ice. Changes in the ocean, ice sheets, and global sea level are projected to be irreversible for centuries to millennia, but reductions in GHG emissions can slow down the rates of change. Furthermore, for higher warming levels, changes in several CIDs would be more widespread and/or pronounced, and more regions are projected to experience concurrent and multiple changes in CIDs.

In Southeast Asia, the increase in the intensity and frequency of hot extremes and the decrease in cold extremes are projected to continue with increasing likelihood with every increment of the global warming level (GWL). There is *medium confidence* that heavy precipitation will intensify in the region, but *low confidence* in future trends in meteorological, agricultural and ecological, and hydrological droughts across GWLs due to inconsistent trends or limited observational evidence. Fewer TCs affecting Southeast Asia are projected, but there is *medium confidence* that the frequency of intense TCs will increase. Furthermore, regional mean sea level will also be higher over longer time periods and for higher emissions scenarios, but with regional variability. Coastal flooding is expected to become more frequent and severe, affecting low-lying coastal areas.

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2.2 Observed Changes and Trends

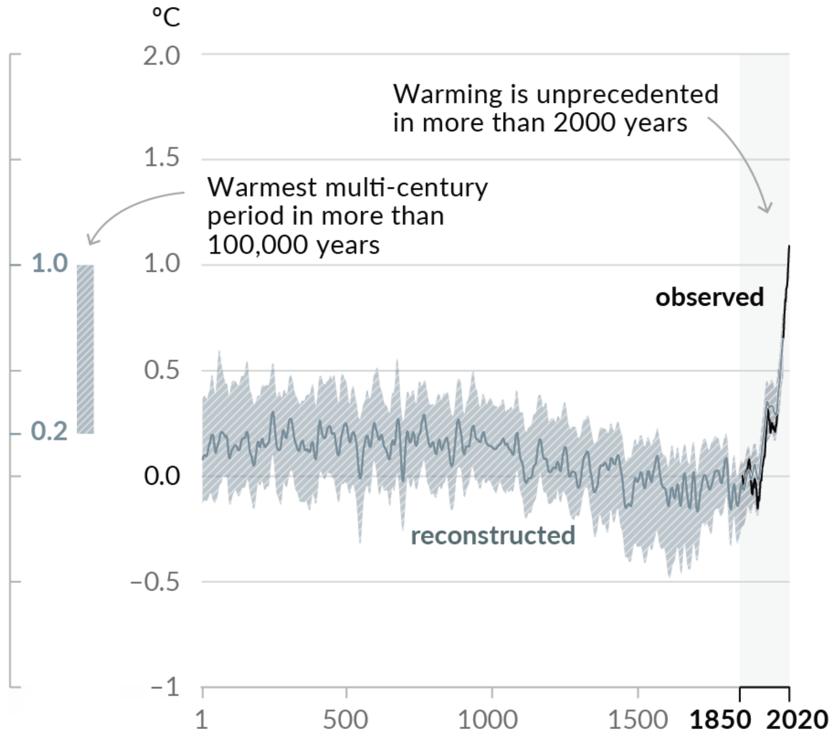
2.2.1 *Global*

Since the Fifth Assessment Report (AR5) of the IPCC in 2013, improvements in observations, paleoclimate records, climate models, and understanding of climate processes have given a clearer perspective of each component of the climate system and its changes, as well as the human influence on these changes. The observed changes in the atmosphere, ocean, cryosphere, and biosphere are widespread, and many of these changes have not been seen in centuries to millennia (Gulev *et al.*, 2021). More significantly, assessing the human influence on the climate system has changed from being "clear" to "an established fact." In addition, anthropogenic climate change is affecting weather and climate extremes in every region (Arias *et al.*, 2021).

An overview of the observed and present changes in selected components of the climate system as summarized in the AR6 is presented in this section.

Figure 2.1

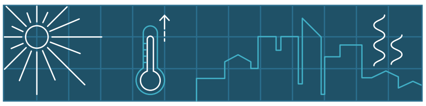
Changes in global mean temperature reconstructed from paleoclimate archives (solid gray line from 1 to 2000) and from direct observations (solid black line from 1850–2020) both relative to 1850–1900 and decadally averaged.



The vertical bar on the left shows the estimated temperature (*very likely* range) during the warmest multi-century period in at least the last 100,000 years, which occurred around 6,500 years ago during the current interglacial period (Holocene). The last interglacial, around 125,000 years ago, is the next most recent candidate for a period of higher temperatures. These past warm periods were caused by slow (multi-millennial) orbital variations. The gray shading with white diagonal lines shows the *very likely* ranges for the temperature reconstructions.

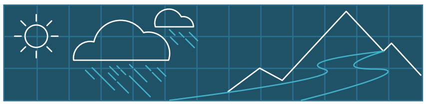
SOURCE: EXTRACTED FROM IPCC (2021A, FIGURE SPM.1A)

2.2.1.1. Temperature



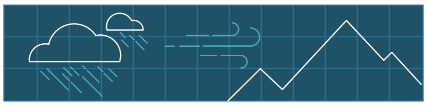
One of the key findings highlighted in the AR6 is the human influence on global warming, as indicated by the rate of increase in global temperature in the last 50 years that has been unprecedented in at least the last 2,000 years (***Figure 2.1***). Improved datasets and methodologies have helped update estimates of the warming since AR5. The human-induced global surface temperature increase from 1850–1900 to 2010–2019 is estimated to be 1.07 °C, with a *likely* range of 0.8 °C–1.3 °C (IPCC, 2021a). Multiple lines of evidence indicate that the observed warming from pre-industrial levels is driven by emissions from human activities, with well-mixed GHGs contributing to a warming of 1.0 °C–2.0 °C, partly offset by a cooling of 0.0 °C–0.8 °C from aerosols. Moreover, natural drivers changed global surface temperature by –0.1 °C to +0.1 °C, whereas contributions from internal variability are estimated at –0.2 °C to +0.2 °C. Global surface temperature was 1.09 °C higher (with a range of 0.95 °C–1.20 °C) in 2011–2020 relative to 1850–1900, with larger increases over land (1.59 °C [with a range of 1.34 °C–1.83 °C]) than over the ocean (0.88 °C [with a range of 0.68 °C–1.01 °C]) (IPCC, 2021a). It is *very likely* that well-mixed GHGs have been the main driver of tropospheric warming since 1979. It is *extremely likely* that human-caused stratospheric ozone depletion mainly drove the cooling of the lower stratosphere between 1979 and the mid-1990s (IPCC, 2021a).

2.2.1.2. Water cycle



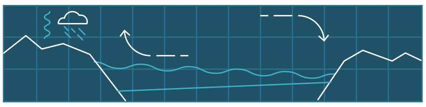
Douville *et al.* (2021) assessed multiple lines of evidence to determine past and present changes in the global water cycle and summarized the findings in the AR6, building on AR5 conclusions and the findings of the three IPCC Special Reports, namely the Special Report on Global Warming of 1.5 °C (SR1.5), Special Report on the Ocean and Cryosphere in a Changing Climate, and Special Report on Climate Change and Land. The global water cycle has intensified since the 1980s (*high confidence*), and these widespread, variable changes since the mid-20th century can be attributed to human-induced global warming and anthropogenic aerosols (*high confidence*). Precipitation over land has *likely* increased since 1950 and has increased at a faster rate since the 1980s (*medium confidence*; IPCC, 2021a). On the other hand, near-surface specific humidity has *likely* increased over the ocean and *very likely* increased over the land since the 1970s, whereas relative humidity has *very likely* decreased in the 2000s (Gulev *et al.*, 2021). However, factors such as high variability and uncertainties in observations pose limits to the detection and attribution of changes in the global water cycle (Douville *et al.*, 2021). A more comprehensive discussion of the processes and drivers involved in the global water cycle can be found in Douville *et al.* (2021).

2.2.1.3. Monsoons



The AR6 reports the contrasting influences of human-induced GHG and aerosol emissions and that of decadal to multidecadal internal variability on observed changes in global and regional monsoon precipitation (IPCC, 2021a). The declining trend (with large multidecadal variability) in global monsoon precipitation noted in the 20th century has changed to a *likely* increase since the 1980s, mainly due to increased summer monsoon precipitation in the Northern Hemisphere caused by increased GHG concentrations and internal variability (*medium confidence*; Gulev *et al.*, 2021). In terms of regional monsoon precipitation, increases in monsoon precipitation in the 20th century over South Asia, East Asia, and West Africa due to the warming effect of GHGs were offset by the cooling effect of anthropogenic aerosols (*high confidence*). On the other hand, there is *medium confidence* in the contribution of increased GHGs and anthropogenic aerosols over Europe and North America to the increase in West African monsoon precipitation since the 1980s (Douville *et al.*, 2021; IPCC, 2021a). Furthermore, changes in the large-scale atmospheric circulation have *likely* occurred since the mid-20th century. For example, near-surface winds have *likely* weakened over land since the 1970s but are *likely* to have strengthened over the ocean during the 1980–2000 period, with some uncertainty in the direction of change after this period (Gulev *et al.*, 2021).

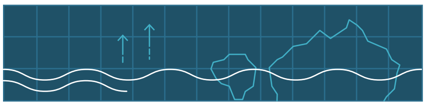
2.2.1.4. El Niño Southern Oscillation and Other Modes of Variability



Except for the Southern Annular Mode, there has been no clear trend since the late 19th century in most major modes of climate variability, including El Niño-Southern Oscillation (ENSO), Pacific Decadal Variability (PDV), and Indian Ocean Dipole (IOD), among others (Douville *et al.*, 2021; Gulev *et al.*, 2021). There is *medium confidence* that the ENSO amplitude and frequency of high-magnitude events since 1950 are higher than in earlier periods but not necessarily outside of centennial-scale variability (Gulev *et al.*, 2021). It was also noted that in the last 20–30 years, there were more El Niño events based in the central Pacific (i.e., El Niño Modoki) than the "classical" events centered in the eastern Pacific. This, however, is not indicative of any long-term change.

There is *high confidence* in the observed interannual and multidecadal changes in the water cycle associated with ENSO and IOD teleconnections in the 20th century (Douville *et al.*, 2021). Xu *et al.* (2023) have also discussed the influence of global warming on the stronger relationship between ENSO and Asian-Australian summer monsoons since 1850. The water cycle is also affected by intra-seasonal variability such as the Madden–Julian Oscillation (MJO) and the Boreal Summer Intraseasonal Oscillation (Douville *et al.*, 2021). The increase in the strength and frequency of the MJO in the mid-20th century (*medium confidence*), which can be attributed partly to global warming and internal variability, has led to changes in regional precipitation (Douville *et al.*, 2021).

2.2.1.5. Sea level and ocean



Global mean sea level

Different processes in the ocean, cryosphere, solid earth, atmosphere, and on land contribute to changes in the sea level (see Box 9.1 and Figure 9.2 of Fox-Kemper *et al.*, 2021). The most recent findings from the AR6 indicate that the rate of increase in global mean sea level (GMSL) since the 20th century is unprecedented in at least the last 3,000 years (*high confidence*; Gulev *et al.*, 2021). GMSL has risen by 0.20 [0.15–0.25] m from 1901–2018 (*high confidence*), and the accelerated rate of rise within this period is evident (Gulev *et al.*, 2021).

It is *very likely* that increases in GMSL since at least 1971 can be attributed to human-caused warming (IPCC, 2021a).

Table 2.1 lists the contributions of different factors to GMSL change during different time periods. The GMSL rise from 1901–2018 is mainly due to mass loss from glaciers (41%) and ocean thermal expansion (38%). Total mass loss from glaciers and ice sheets contributed more to the recent increase from 2006–2018 (*high confidence*; Fox-Kemper *et al.*, 2021).

Table 2.1

Observed contributions to global mean sea level (GMSL) change for five different periods

OBSERVED CONTRIBUTION TO GMSL CHANGE		1901–1990	1971–2018	1993–2018	2006–2018	1901–2018
Thermal Expansion	**Δ (mm)**	31.6 (31.9%) [14.7 to 48.5]	47.5 (50.4%) [34.3 to 60.71]	32.7 (45.9%) [23.8 to 41.6]	16.7 (38.6%) [8.9 to 24.6]	63.2 (38.4%) [47.0 to 79.4]
	mm/yr	0.36 [0.17 to 0.54]	1.01 [0.73 to 1.29]	1.31 [0.95 to 1.66]	1.39 [0.74 to 2.05]	0.54 [0.40 to 0.68]
Glaciers (excluding peripheral glaciers)	**Δ (mm)**	5.18 (52.3%) [304 to 73.2]	20.9 (22.2%) [10.0 to 31.7]	13.8 (19.4%) [100 to 17.6]	7.5 (17.3%) [6.8 to 8.2]	67.2 (40.8%) [41.8 to 92.6]
	mm/yr	0.58 [0.34 to 0.82]	0.44 [0.21 to 0.67]	0.55 [0.40 to 0.70]	0.62 [10.57 to 0.68]	0.57 [0.36 to 0.79]
Greenland ice sheet (including peripheral glaciers)	**Δ (mm)**	29.0 (29.3%) [16.3 to 41.7]	11.9 (12.6%) [7.7 to 16.1]	10.8 (15.2%) [89 to 12.7]	7.5 (17.3%) [6.2 to 8.9]	40.4 (24.5%) [27.2 to 53.5]
	mm/yr	0.33 [0.18 to 0.47]	0.25 [0.16 to 0.34]	0.43 [0.36 to 0.51]	0.63 [0.51 to 0.74]	0.35 [0.23 to 0.46]
Antartic ice sheet (including peripheral glaciers)	**Δ (mm)**	04 (0.4%) [-8.8 to 9.6]	6.7(7.196) [-4.0 to 17.3]	61(8.6%) [4.0 to 8.3]	4.4(10.2%) [2.9 to 6.0]	6.7 (4.1%) [-4.0 to 17.4]
	mm/yr	0.00 [-0.10 to 0.11]	0.14 [-0.09 to 0.37]	0.25 [0.16 to 0.33]	0.37 [0.24 to 0.50]	0.06 [-0.03 to 0.15]
Land water storage*	**Δ (mm)**	- 13.8 (-13.9%) [-31.4 to 3.8]	7.3 (7.7%) [-2.4 to 16.9]	7.8 (10.9%) [3.3 to 12.2]	7.2 (166%) [3.8 to 10.6]	- 12.9 (-7.8%) [-45.8 to 20.0]
	mm/yr	-0.15 [-0.35 to 0.04]	0.15 [-0.05 to 0.36]	0.31 [0.13 to 0.49]	0.60 [0.32 to 0.88]	-0.11 [-0.39 to 0.17]
Sum of observed contributions	**Δ (mm)**	99.0 [63.0 to 135.1]	94.2 [715 to 117.0]	71.2 [60.2 to 82.3]	43.4 [34.5 to 52.2]	164.6 [116.9 to 212.4]
	mm/yr	1.11 [0.71 to 1.52]	2.00 [1.52 to 2.49]	2.85 [2.41 to 3.29]	3.61 [2.88 to 4.35]	1.41 [1.00 to 1.82]
Observed GMSL change	**Δ (mm)**	120.1T [69.3 to 170.8]	09.6T/A [728 to 146.4]	81.2A [721 to 90.2]	44.3A [38.6 to 50.0]	201.9T/A [150.3 to 253.5]
	mm/yr	1.35T [0.78 to 1.92]	2.33T/A [1.55 to 3.12]	3.25A [2.88 to 3.61]	3.69A [3.21 to 4.17]	1.73T/A [1.28 to 2.17]

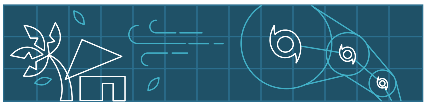
Values are expressed as the total change in the annual mean or year mid-point value over each period (mm) along with the equivalent rate (mm yr^{-1}). The *very likely* ranges appear in brackets based on the various section assessments, as indicated. Uncertainties for the sum of contributions are added in quadrature, assuming independence. Percentages are based on the central estimate of contributions compared to the central estimate of the sum of contributions.

SOURCE: TABLE 9.5 IN FOX-KEMPER *et al.* (2021)

Ocean

In AR6, observed changes in the ocean are described as widespread and unprecedented for centuries to millennia (*high confidence*) and have been attributed mainly to human influence (Gulev *et al.*, 2021; IPCC, 2021a). Global ocean heat content has increased since the 1970s, and this warming is *virtually certain* for the upper layer (0–700 m; Gulev *et al.*, 2021). The average increase in ocean surface temperature in 2011–2020 from pre-industrial levels is estimated at 0.88 °C (0.68 °C–1.01 °C) (Fox-Kemper *et al.*, 2021). The intensification of the upper ocean salinity contrasts since the 1950s, the increase in upper ocean stratification since 1970, and the global surface ocean acidification over the past four decades are all *virtually certain* (Arias *et al.*, 2021; Gulev *et al.*, 2021). There is also *high confidence* in the deoxygenation of many open ocean areas since the mid-20th century (Arias *et al.*, 2021; Gulev *et al.*, 2021). Marine heatwaves (MHWs) have become more frequent in the 20th century (*high confidence*), with increased intensity and duration since the 1980s (*medium confidence*; Arias *et al.*, 2021; Fox-Kemper *et al.*, 2021).

2.2.1.6. Climatic impact-drivers



AR6 introduced CIDS as a more neutral way to refer to conditions in the physical climate, as described by means, events, or extremes, which would have impacts on society or ecosystems (Ranasinghe *et al.*, 2021). The seven CID types include heat and cold; wet and dry; wind; snow and ice; coastal; open ocean; and other. The regional chapters of AR6 WG1, namely Chapter 12 (Ranasinghe *et al.*, 2021) and the Atlas (Gutiérrez *et al.*, 2021a), adopted the CID framework (Ruane *et al.*, 2022), and assessed information on CIDs for different regions and sectors to support and link changes in the physical climate to the AR6 WG2 assessment of impacts and risks (or opportunities). Although CIDs, which include extreme climate events and some of the climate variables discussed in the previous sections, can lead to adverse, beneficial, mixed, or neutral outcomes, focus in this section is given to CIDs connected to hazards, particularly climate extremes (as discussed in Seneviratne *et al.*, 2021).

The report's assessment is that the present climate in most regions is already different from the climate of the early or mid-20th century (Ranasinghe *et al.*, 2021). In most regions, CIDs have changed in terms of magnitude, frequency, duration, seasonality, and spatial extent of associated indices (*high confidence*). Some of these changes and the increased frequency of compound extreme events (e.g., concurrent heatwaves, droughts, and compound flooding) since the 1950s have been attributed to human influence (IPCC, 2021b; Ranasinghe *et al.*, 2021). Changes in mean and extreme temperatures over land, as well as ocean acidification and deoxygenation, are noted to be outside of observed natural variability (*high confidence*). For other CIDs such as precipitation and drought, changes are anticipated to emerge from natural variability in the 21st century, where the timing depends on the emissions scenario. However, there are still CIDs such as hail, severe storms, and dust storms where the poor quality and coverage of observations and limitations in modeling result in *low confidence* in the assessment of change (Ranasinghe *et al.*, 2021).

It is *virtually certain* that since the 1950s, the human-induced greenhouse effect has been the main cause of the increase in the frequency and intensity of hot extremes and the decrease of cold extremes on the global scale (IPCC, 2021b; Seneviratne *et al.*, 2021). Temperature trends were also affected by anthropogenic aerosols, land use change, and multidecadal natural variability. MHWs are also observed to have occurred twice as often since the 1980s (*high confidence*; IPCC, 2021b). Human-induced climate change has also caused increases in the frequency and intensity of heavy precipitation events over land (*high confidence*) and increases in agricultural and ecological droughts in some regions because of higher evapotranspiration over land (*medium confidence*) since the 1950s (Seneviratne *et al.*, 2021).

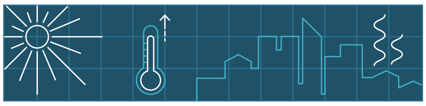
There is *low confidence* in long-term trends in TCs and severe convective storms, such as hail and severe winds, which are constrained by data (IPCC, 2021b; Seneviratne *et al.*, 2021). However, it is *likely* that the global proportion of major (Categories 3–5) TCs and the global frequency of TC rapid intensification events have increased over the past 40 years (Seneviratne *et al.*, 2021). It was also noted that in the Western North Pacific Ocean, the location where TCs reach their peak intensity has shifted northward since the 1940s (Seneviratne *et al.*, 2021).

2.2.2 *Southeast Asia*

The most recent findings for the Southeast Asian region are drawn from the IPCC AR6 WG1, specifically the Technical Summary. More literature is now available since the AR5 because of regional initiatives such as the Coordinated Regional Climate Downscaling Experiment (CORDEX). These initiatives have given information on observed changes in mean climate and extremes as well as their projected changes.

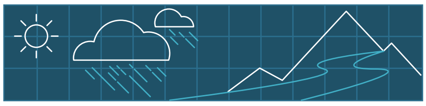
In Southeast Asia, observation records indicate that the intensity and frequency of hot extremes and cold extremes have significantly increased and decreased, respectively, which can be attributed to human activities (*high confidence*; Table 11.7 in Seneviratne *et al.*, 2021). Heavy precipitation events have intensified in the region (*medium confidence*; Table 11.8 in Seneviratne *et al.*, 2021). On the other hand, there is *low confidence* in the observed trends in meteorological drought, agricultural and ecological drought, and hydrological drought due to inconsistent trends between subregions, indices used, and/or limited evidence (Table 11.9 in Seneviratne *et al.*, 2021). Fewer and more destructive TCs have affected Southeast Asia, but there has been no long-term trend in the number of TCs (Ranasinghe *et al.*, 2021).

2.2.2.1. Temperature



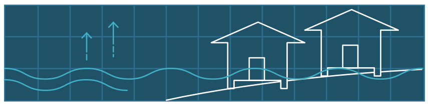
Annual mean surface temperature has been observed to increase across Asia during 1960–2015, and it has accelerated after the 1970s (*high confidence*). The minimum temperature has a higher rate of warming compared to the maximum temperature, resulting in more frequent warm nights and warm days and less frequent cold days and cold nights (*high confidence*; Ranasinghe *et al.*, 2021).

2.2.2.2. Water cycle



Observed mean rainfall trends in Southeast Asia have no spatial coherence or consistency across datasets and seasons (*high confidence*), although most of the region experienced an increase in rainfall intensity with a reduced number of wet days (*medium confidence*; Arias *et al.*, 2021). The South and Southeast Asian monsoons have weakened in the second half of the 20th century (*high confidence*; Douville *et al.*, 2021). The dominant cause of the observed decrease in precipitation of the South and Southeast Asian monsoons since the mid-20th century is anthropogenic aerosol forcing.

2.2.2.3. Regional sea level



Based on tide gauge reconstruction, the rate of relative sea level rise (RSLR) over 1900–2018 has been estimated to be 1.33 [0.80–1.86] mm yr^{-1} in the Indian Ocean–Southern Pacific and 1.68 [1.27–2.09] mm yr^{-1} in the Northwest Pacific (Ranasinghe *et al.*, 2021). RSLR is higher in the 1993–2018 period, with values of 3.65 [3.23–4.08] mm yr^{-1} and 3.53 [2.64–4.45] mm yr^{-1}, respectively, based on satellite altimetry 2020; Ranasinghe *et al.*, 2021). There is also *medium confidence* in the fast rise in sea levels in the Western Pacific in this 1993–2018 period (Fox-Kemper *et al.*, 2021). However, land subsidence due to groundwater extraction can affect estimates of RSLR in many coastal areas in Asia, such as in the Mekong delta region (Ranasinghe *et al.*, 2021).

Table 2.2

Regional summary of observed trends in climatic impact-drivers (CIDs) that are broadly relevant for Southeast Asia

CID		OBSERVED TREND / HUMAN ATTRIBUTION
Heat and cold	Mean air temperature	▲ Upward trend / No attribution
	Extreme heat	▲ Upward trend / *High confidence* of attribution
	Cold spell	▼ Downward trend / *High confidence* of attribution
Wet and dry	Mean precipitation	*Low confidence* in trend and attribution
	River flood	*Low confidence* in trend and attribution
	Heavy precipitation and pluvial flood	▲ Upward trend / No attribution
	Landslide	*Low confidence* in trend and attribution
	Aridity	*Low confidence* in trend and attribution
	Hydrological drought	*Low confidence* in trend and attribution
	Agricultural and ecological drought	*Low confidence* in trend and attribution
	Fire weather	*Low confidence* in trend and attribution
Wind	Mean wind speed	*Low confidence* in trend and attribution
	Severe wind storm	*Low confidence* in trend and attribution
	Tropical cyclone	▲ Upward trend / No attribution
	Sand and dust storm	*Low confidence* in trend and attribution
Snow and ice	Hail	*Low confidence* in trend and attribution
Coastal and oceanic	Relative sea level	▲ Upward trend / No attribution
	Coastal flood	*Low confidence* in trend and attribution
	Coastal erosion	*Low confidence* in trend and attribution
	Marine heatwave	▲ Upward trend / No attribution
	Ocean and lake acidity	*Low confidence* in trend and attribution
Others	Air pollution weather	*Low confidence* in trend and attribution
	Atmospheric CO_2 at surface	▲ Upward trend / No attribution
	Radiation at surface	*Low confidence* in trend and attribution

SOURCES: ADAPTED FROM TABLE TS.5 IN ARIAS *et al.* (2021) AND IPCC WGI INTERACTIVE ATLAS: REGIONAL SYNTHESIS (GUTIÉRREZ *et al.*, 2021B; ITURBIDE *et al.*, 2021)

2.2.2.4. Climatic impact-drivers

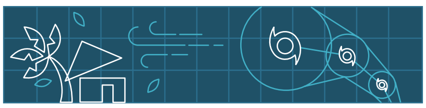


Table 2.2 summarizes the observed trend and confidence assessment of the human attribution to this trend in CIDs that are broadly relevant for Southeast Asia, which was adapted from Table TS.5 of Arias *et al.* (2021). Apart from the changes in the CIDs discussed above, it is important to note that fewer and more destructive TCs have affected Southeast Asia, but there is no long-term trend in the number of TCs. Furthermore, there is currently *low confidence* in the direction of observed trends and/or attribution for many CIDs in Southeast Asia, which can be due to limited evidence and/or limited agreement in the direction of change.

2.3 Climate Projections

2.3.1 *Global*

This section summarizes the key findings of the IPCC AR6 WG1 report, particularly on projected changes in the climate and CIDs. ***Table 2.3*** lists the estimated range of values of projected changes in selected climate indicators by the end of the 21st century under the different shared SSPs.

Table 2.3

Projected changes in the climate at the end of the 21st century under five illustrative emissions scenarios.

SCENARIO	GLOBAL SURFACE TEMPERATURE (°C)	AVERAGE ANNUAL GLOBAL LAND PRECIPITATION (%)	GLOBAL MEAN SEA LEVEL (m)
	Very likely range of change, in late-century (2081–2100) relative to 1850–1900	*Likely* range of change, in late-century (2081–2100) relative to 1995–2014	*Likely* range of change by 2100 relative to 1995–2014
SSP1-1.9: very low emission scenario	1.0–1.8	0–5	0.28–0.55
SSP1-2.6: low emission scenario	1.3–2.4	0–7	0.32–0.62
SSP2-4.5: intermediate emission scenario	2.1–3.5	1.5–8	0.44–0.76
SSP3-7.0: high emission scenario	2.8–4.6	0.5–10	**
SSP5-8.5: very high emission scenario	3.3–5.7	1–13	0.63–1.01 m

SOURCES: GLOBAL SURFACE TEMPERATURE (EXTRACTED FROM IPCC AR6 - WG1 SPM TABLE SPM.1), AVERAGE ANNUAL GLOBAL LAND PRECIPITATION (EXTRACTED FROM IPCC AR6 – WG1 SPM B.3.1 AND CHAPTER 4 EXECUTIVE SUMMARY – PRECIPITATION), AND GMSL (EXTRACTED FROM IPCC AR6 - WGI SPM B.5.3) (ARIAS ET AL., 2021).

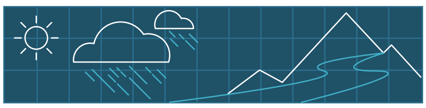
2.3.1.1. Temperature

The global surface temperature will continue to increase under all emissions scenarios. Under the very low and low emissions scenario, global surface temperature is *very likely* to be higher by 1.0 °C–1.8 °C and 1.3 °C–2.4 °C, respectively, compared to 1850–1900 in the long term (2081–2100). Meanwhile, for higher emissions scenarios, the projected changes in global surface temperature are also greater: 2.1 °C–3.5 °C for the intermediate emissions scenario, 2.8 °C–4.6 °C for the high emissions scenario, and 3.3 °C–5.7 °C for the very high emissions scenario (IPCC AR6 - WGI SPM B.1.1).

Across all emissions scenarios (except the very high emissions scenario), the 20-year averaged global surface temperature will cross the 1.5 °C limit in the early 2030s (Cross-Section Box TS.1; Arias *et al.*, 2021).

Unless deep reductions in emissions occur in the coming decades, GWLs of 1.5 °C and 2 °C will be exceeded during the 21st century (IPCC AR6 - WGI SPM B.1), with every increment of global warming increasing the frequency and intensity of climate extremes (IPCC AR6 - WGI SPM B.2.2). Nonetheless, it is *virtually certain* that rapid and substantial reductions in global GHG emissions can limit global surface temperature rise and associated changes (TS.2.1; Arias *et al.*, 2021).

2.3.1.2. Water cycle



Average annual global land precipitation

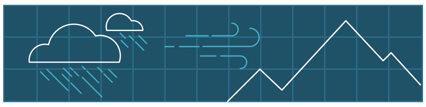
Focusing on land precipitation, which has greater social relevance compared to global precipitation, AR6 projects with *high confidence* that average annual global land precipitation will continue to increase toward the end of the century (2081–2100) relative to 1995–2014 under all emissions scenarios as the global water cycle continues to intensify with rising temperatures. For the very low emissions scenario (SSP1-1.9), the *likely range* of precipitation anomalies is 0%–5%. However, for the intermediate (SSP2-4.5), high (SSP3-7.0), and very high (SSP5-8.5) emissions scenarios, *likely* ranges are 1.5%–8%, 0.5%–10%, and 1%–13% by 2081–2100 relative to 1995–2014. For these three scenarios, it is also *very likely* that precipitation will increase over high latitudes, the equatorial Pacific, and parts of the monsoon regions while decreasing over parts of the subtropics and limited areas in the tropics (IPCC AR6 - WGI SPM B.3.1).

Over most land regions, precipitation and surface water flows are projected to become more variable within seasons (*high confidence*) and from year to year (*medium confidence*). There is also an increasing portion of global land experiencing detectable increases or decreases in seasonal precipitation (*medium confidence*; IPCC AR6 - WGI SPM B.3.1).

With increasing temperatures, precipitation over land is expected to increase more rapidly than precipitation over the ocean (*high confidence*) and to contribute to a gradual increase in global mean precipitation. For every 1 °C of warming, annual mean and global mean precipitation will *very likely* increase by 1%–3% (IPCC AR6 - WGI, Chapter 4 - 4.5.1.4).

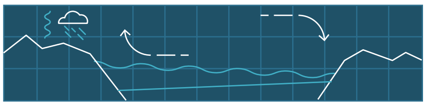
There is also *high confidence* that a warmer climate can result in more severe wet events by increasing the near-surface atmospheric water holding capacity, as well as more severe dry events by increasing atmospheric evaporative demand. However, the occurrence and frequency of these extreme events are affected by changes in atmospheric circulation patterns (Douville *et al.*, 2021).

2.3.1.3. Monsoons



Based on the IPCC AR6 WGI, it is *likely* that global land monsoon precipitation will increase this century with continued global warming, particularly in the Northern Hemisphere, even though monsoon circulation is projected to weaken. The warming-induced strengthening of precipitation in monsoon regions is partly offset by the slowdown of the tropical circulation due to global warming (*high confidence*). Near-term changes in the global monsoon are dominated by internal variability and model uncertainties (*medium confidence*). Long-term changes, on the other hand, are characterized by north–south and east–west asymmetry of global monsoon rainfall change. The Northern Hemisphere will have a greater increase compared to the Southern Hemisphere. While there are enhanced Asian-African monsoons opposite a weakened North American monsoon (*medium confidence*), there is *low confidence* in future changes in the South American and Australian-Maritime Continent monsoons (Box TS.13, Arias *et al.*, 2021). Projections for monsoon regions are indicated by contrasting and uncertain precipitation and circulation changes.

2.3.1.4. El Niño Southern Oscillation and other modes of variability



In the future, it is *virtually certain* that the ENSO will still be the dominant mode of interannual variability. While there is no consensus on projected changes in the intensity of ENSO-related sea surface temperature (SST) variability (*medium confidence*), it is *very likely* that ENSO-related rainfall variability will be enhanced significantly by the latter half of the 21st century under the intermediate, high, and very high emissions scenarios. Furthermore, it is *very likely* that ENSO-related rainfall variability will result in significant regional changes (see ***Figure 2.2***; TS.4.2.2; Arias *et al.*, 2021). There is also *medium confidence* that the Atlantic Multi-decadal Variability will undergo a negative phase shift in the near term (2021–2040) and *medium confidence* in the decrease in variance of the PDV in the long term.

Figure 2.2

Assessment of modes of variability

	NAM	SAM	ENSO	IOB	IOD	AZM	AMM	PDV	AMV
Past changes since the start of observations	1960s 1990s 2010s Boreal winter {2.4.1.1}	1950s 2000s Austral summer {2.4.1.2}	1400–1850 Since 1950s {2.4.2}	Within proxy-inferred variability range {2.4.3}	Within proxy-inferred variability range {2.4.3}	*Limited evidence* {2.4.4}	*Limited evidence* {2.4.4}	Dominated by multi-decadal fluctuations {2.4.5}	Dominated by multi-decadal fluctuations {2.4.6}
CMIP5 and CMIP6 model performance	High performance {3.7.1}	High performance {3.7.2}	Medium performance {3.7.3}	Medium performance {3.7.4}	Medium performance {3.7.4}	Low performance {3.7.5}	Low performance {3.7.5}	Medium performance {3.7.6}	Medium performance {3.7.7}
Human influence on the observed changes	No robust evidence {3.7.1}	Contributed through GHG (all seasons) & ozone (DJF) {3.7.2}	*Low agreement* {3.7.3}	No robust evidence {3.7.4}	Not detected {3.7.4}	No robust evidence {3.7.5}	No robust evidence {3.7.5}	Not detected {3.7.6}	Contributed through aerosols {3.7.7}
Near-term future changes (2021–2040)	Internal variability dominates {4.4.3.1}	All seasons except DJF {4.4.3.1}	Internal variability dominates {4.4.3.2}	No robust evidence {4.4.3.3}	No robust evidence {4.4.3.3}	No robust evidence {4.4.3.4}	No robust evidence {4.4.3.4}	*Limited evidence* {4.4.3.5}	+ – Phase shift from + to – {4.4.3.6}
Mid-to-long-term future changes (2041–2100)	SSP5-8.5 SSP3-7.0 DJF SSP1-2.6 SSP1-1.9 {4.3.3.1; 4.5.3.1}	SSP5-8.5 SSP3-7.0 All seasons SSP1-1.9 DJF {4.3.3.1; 4.5.3.1}	Increase in precipitation variance {4.3.3.2; 4.5.3.2}	No robust evidence {4.5.3.3}	increase in extreme positive events {4.5.3.3}	No robust evidence {4.5.3.4}	No robust evidence {4.5.3.4}	Decrease in variance {4.5.3.5}	No changes {4.5.3.6}

low confidence | *medium confidence* | *high confidence*

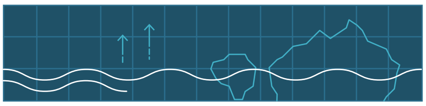
more likely than not | *likely* | *very likely*

LIST OF ABBREVIATIONS:

NAM - Northern Annular Model
SAM - Southern Annular Mode
ENSO - El Niño Southern Oscillation
IOB - Indian Ocean Basin
IOD - Indian Ocean Dipole
AZM - Atlantic Zonal Mode
AMM - Atlantic Meridional Mode
PDV - Pacific Decadal Variability
AMV - Atlantic Multi-decadal Variability

SOURCE: ARIAS *et al.* (2021)

2.3.1.5. Sea level and ocean



Global mean sea level

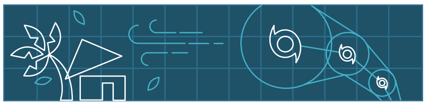
It is *virtually certain* that GMSL will continue to rise over the 21st century. The increase is primarily caused by human-induced global warming, which causes thermal expansion and mass loss from glaciers and ice sheets. By 2100, GMSL will rise by 0.28–0.55 m relative to 1995–2014 under the very low emissions scenario, 0.32–0.62 m under the low emissions scenario, 0.44–0.76 m under the intermediate emissions scenario, and 0.63–1.01 m under the very high emissions scenario (*likely* ranges). However, it is worth noting that these *likely* ranges do not include ice sheet–related processes marked by deep uncertainty, with earlier-than-projected disintegration of marine ice shelves potentially leading to higher amounts of GMSL rise. Beyond 2100, there is also *high confidence* that GMSL is committed to rise for centuries to millennia due to continuing deep ocean warming and ice sheet melt and will remain elevated for thousands of years (Box TS.4; Arias *et al.*, 2021; IPCC AR6 WG1 SPM B.5.3).

Ocean

SST is *virtually certain* to continue increasing in the 21st century at a rate depending on future emission scenarios. It is *very likely* that at least 83% of the world's ocean surface will have warmed by 2100 under the low emission scenario and at least 98% under the very high emission scenario. Likewise, MHWs (days exceeding the 99th percentile in SST from 1982–2016) are projected to become four times more frequent by 2081–2100 (compared to 1995–2014) under the low emission scenario or eight times more frequent under the very high emission scenario. While permanent MHWs (more than 360 days per year) are projected to occur in parts of the tropical ocean, Arctic Ocean and around 45°S in the 21st century under the very high emission scenario, these MHWs can be largely avoided under the low emission scenario (Fox-Kemper *et al.*, 2021).

There is also very *high confidence* that the ocean will continue to take up heat in the coming decades under all future emission scenarios, and there is *high confidence* that there is a long-term commitment (essentially irreversible on human timescales) to increased ocean heat content (Bindoff *et al.*, 2019). Compared with the observed changes since the 1970s, it is *likely* that ocean heat content will increase two to four times under the low emission scenario or four to eight times under the very high emission scenario (Fox-Kemper *et al.*, 2021).

2.3.1.6. Climatic impact-drivers



Increasing global warming and climate risks

Under the very low emissions scenario, global surface temperature is estimated to be higher by around 1.5 °C relative to 1850–1990 in the short term (2021–2040), 1.6 °C in the mid term (2041–2060), and 1.4 °C in the long term (2081–2100). It is the only illustrative scenario where the GWL of 1.5 °C is reached only temporarily, as the estimated overshoot of no more than 0.1 °C is *more likely than not* to decline back to below 1.5 °C toward the end of the 21st century. Meanwhile, under the low emissions scenario, the 1.5 °C level is *more likely than not* to be exceeded, although the 2.0 °C level remains *unlikely* to be exceeded. However, both the GWLs of 1.5 °C and 2.0 °C would be exceeded under the intermediate, high, and very high emissions scenarios, with the crossing of the 2.0 °C level projected to occur in the mid-term (see ***Table 2.4***; IPCC AR6 WG1 SPM B.1.2 and B.1.3). To remain below the 1.5 °C GWL, deep cuts in GHG emissions need to be made immediately and over the coming decades, following the emissions pathway of the very low emissions scenario.

Table 2.4

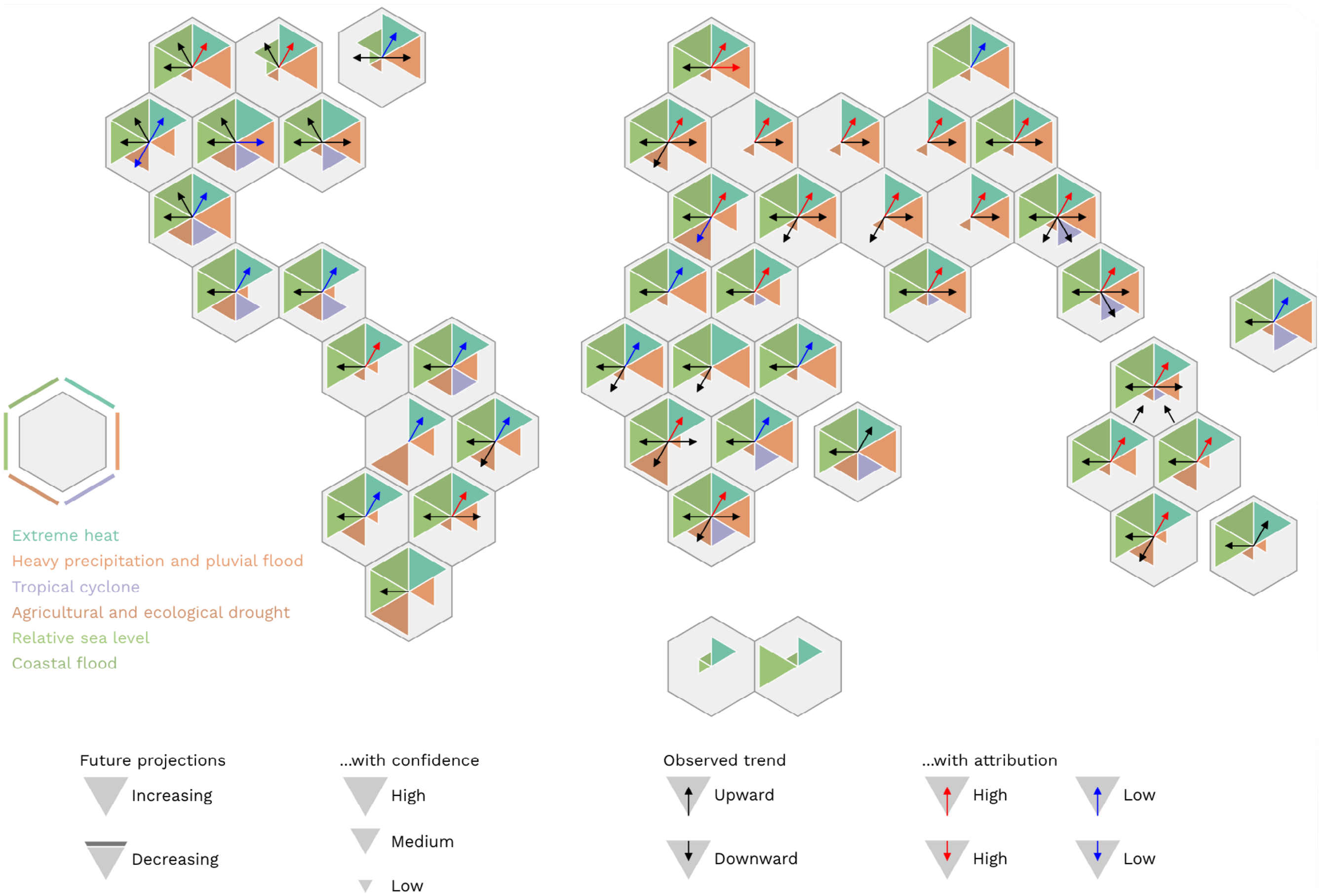
Likelihood of crossing the 1.5 °C and 2.0 °C global warming level (GWL) under the five illustrative emissions scenarios

SCENARIO	1.5 °C GWL	2.0 °C GWL
SSP1-1.9: very low emissions scenario	More likely than not to be reached (*also more likely than not to decline back to below 1.5 °C in long-term*)	Extremely unlikely to exceed
SSP1-2.6: low emissions scenario	More likely than not to exceed	Unlikely to exceed
SSP2-4.5: intermediate emissions scenario	Likely to exceed	Extremely likely to exceed (*more likely than not to occur during mid-term*)
SSP3-7.0: high emissions scenario	Likely to exceed	Would exceed (*likely during mid-term*)
SSP5-8.5: very high emissions scenario	Very likely to exceed	Would exceed (*very likely during mid-term*)

SOURCE: IPCC AR6 - WG1 SPM B.1.2 AND B.1.3; CROSS-SECTION BOX TS.1; ARIAS *et al.* (2021)

Figure 2.3

Projected changes in several climatic impact-drivers around 2050 consistent with a 2 °C global warming level (relative to 1850–1990).



The regional information presented is representative of average changes within the whole region.

SOURCE: GUTIÉRREZ *et al.* (2021B) AND ITURBIDE *et al.* (2021)

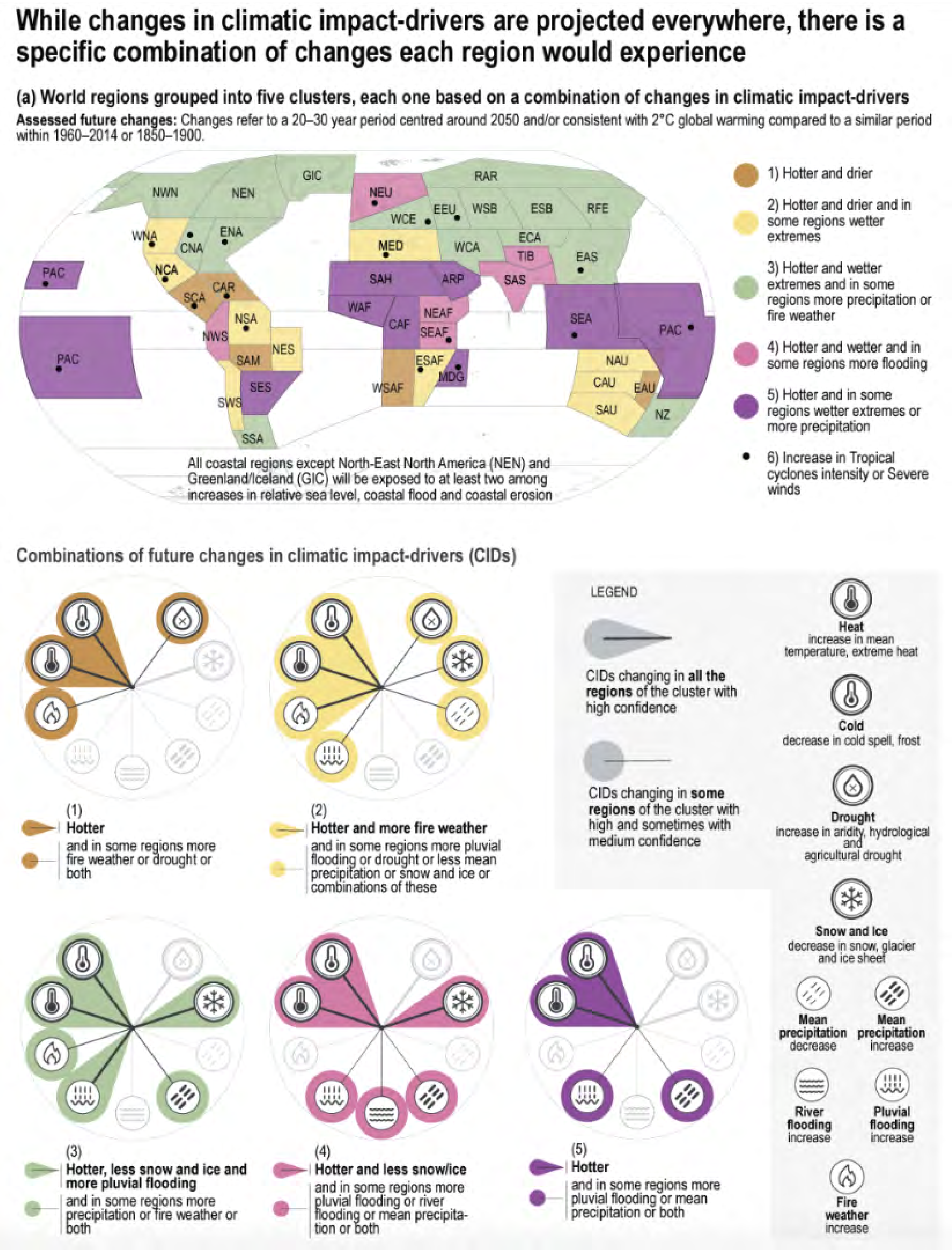
At the global level, changes in the climate system become more pronounced with increasing global warming. With additional global warming, even at the 1.5 °C GWL, there will be an increasing occurrence of some extreme events unprecedented in the observational record. For example, every additional 0.5 °C will cause clearly discernible increases in the frequency and intensity of extreme events such as heat waves (*very likely*), heavy precipitation (*high confidence*), and agricultural and ecological droughts in some regions (*high confidence*). Projected changes in frequency are also higher for rarer events (*high confidence*; IPCC AR6 WG1 SPM B.2.2). Meanwhile, with every additional global warming of 1 °C, extreme daily precipitation events are projected to intensify by about 7% (*high confidence*). Intense TCs (Categories 4 and 5) are also projected to increase in frequency, and the peak wind speeds of the most intense TCs are likewise expected to increase at the global scale with increasing global warming (*high confidence*; IPCC AR6 WG1 SPM B.2.4).

Similarly, at the regional level, climatic changes will also become more notable with increasing global warming (***Figure 2.3***). There is *high confidence* that all regions will experience further increases in hot CIDs and decreases in cold CIDs, with more regions experiencing changes across more CIDs at the 2 °C GWL or higher than at 1.5 °C (*high confidence*). At higher GWLs, extreme heat thresholds relevant to agriculture and health are also projected to be exceeded more frequently (*high confidence*; IPCC AR6 WG1 SPM C.2.1). Regional mean RSL will continue to rise throughout the 21st century (*very likely to virtually certain*), which is projected to increase the frequency of extreme sea level events. For example, extreme sea level events that occurred once per century in the recent past will occur at least annually by 2100 at more than half of all tide gauge locations (*high confidence*; IPCC AR6 WG1 SPM C.2.5).

Different regions will also experience different combinations of CIDs. Arias *et al.* (2021) grouped world regions into five clusters, each one based on a combination of changes in CIDs. Assessed future changes refer to a 20-30 year period centered around 2050 that is consistent with a 2 °C global warming compared to a similar period within 160-2014 pr 1850–1900. In Southeast Asia, the future is projected to be hotter with higher precipitation averages or extremes (***Figure 2.4***).

Figure 2.4

Combinations of climatic impact-drivers different regions would experience



EXTRACTED FROM FIGURE TS.22A IN ARIAS *et al.* (2021)

2.3.2 *Southeast Asia*

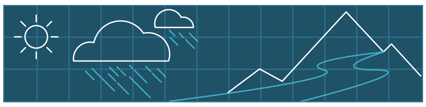
In comparison to the earlier IPCC assessments, there is a more regional focus in the AR6, comprising about a third of the climate report. This is a result of a substantial increase in the science and literature concerning regional climate change, such as in Southeast Asia, where there has been progress in observational data analysis and downscaling activities, especially in recent decades (Tangang *et al.*, 2021).

In Southeast Asia, the mean temperature is projected to increase slightly less than the global average (Arias *et al.*, 2021). AR6 reports that the increase in the intensity and frequency of hot extremes, and decrease in cold extremes in Southeast Asia will continue in the future with increasing likelihood with every increment of GWL, such that these trends are *virtually certain* in a 4 °C GWL relative to the 1995–2014 period (Table 11.7 in Seneviratne *et al.*, 2021). There is spatial variability in future rainfall change in the region, such that rainfall will increase in the northern parts and decrease in the Maritime Continent (*medium confidence*; Arias *et al.*, 2021). Heavy precipitation in the region will intensify with *medium confidence* under a 1.5 °C GWL, but with *higher confidence* above 2 °C GWL, relative to the 1995–2014 period (Table 11.8 in Seneviratne *et al.*, 2021). There is *low confidence* in future trends in meteorological drought due to limited evidence and inconsistent trends depending on models, subregions, and studies under a 1.5 °C GWL and a 2 °C GWL, respectively. However, there is a projected increase in drying conditions over Southeast Asia under a 4 °C GWL (*medium confidence*). On the other hand, there is *low confidence* in future trends in agricultural and ecological drought and hydrological drought across GWLs due to inconsistent trends or limited evidence (Table 11.9 in Seneviratne *et al.*, 2021). RSLR is projected to *very likely* continue in the Southeast Asian region, but with regional variability, and could increase the chance of coastal flooding. Furthermore, fewer TCs affecting Southeast Asia are projected, but the frequency of intense TCs will increase (*medium confidence*).

2.3.2.1. Temperature

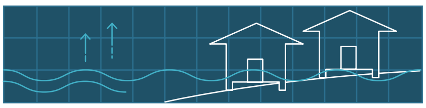
Climate projections indicate that the observed warming over Southeast Asia will continue with a projected increase of less than 5 °C by the end of the 21st century under RCP 8.5/SSP5-8.5 (Ranasinghe *et al.*, 2021), with a lower magnitude of warming under a lower emission scenario (Supharatid *et al.*, 2022). As shown in the IPCC AR6 Interactive Atlas, the range of average mean temperature increase over land in Southeast Asia ranges from 0.7 °C to 1.3 °C (0.7 °C–1.8 °C) under RCP 2.6 (SSP1-2.6) to 2.8 °C to 4.4 °C (2.6 °C–4.8 °C) under RCP 8.5 (SSP5-8.5) based on Coupled Model Intercomparison Project Phase 5 (CMIP5) model projections (Gutierrez *et al.*, 2021a). This future warming is *likely* slightly lower than the global mean (Gutierrez *et al.*, 2021a). More warm days and nights are projected at 2 °C GWL compared to 1.5 °C GWL, particularly in the dry season (Zhu *et al.*, 2020).

2.3.2.2. Water cycle



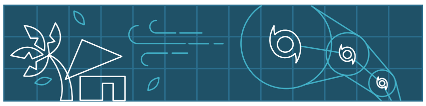
In Southeast Asia, future changes in rainfall vary depending on the area, season, and climate model (Gutierrez *et al.*, 2021a). Both the CMIP5 and CMIP6 global models project increases in annual mean rainfall over most land areas in the region, with strong model agreement at higher warming levels. On the other hand, downscaled projections from CORDEX Southeast Asia indicate future increases in December to February rainfall in the region ranging from 5%-20%, except for the rainfall decline over the Maritime Continent, whereas significantly drier conditions are projected during June to August, except over Myanmar and northern Borneo (Gutierrez *et al.*, 2021a).

2.3.2.3. Regional sea level



Regional mean RSLR is *very likely* to continue in the Southeast Asian region, although this may be underestimated due to the partial representation of land subsidence (Ranasinghe *et al.*, 2021). Median values of the projected RSLR for Southeast Asia range from 0.4 m under SSP1-2.6 to 0.7 m under SSP5-8.5 for 2081–2100 relative to 1995–2014 (Gutiérrez *et al.*, 2021b).

2.3.2.5. Climatic Impact-Drivers



As global temperatures increase, extreme temperatures in Southeast Asia will also shift toward warming, which can increase heat stress in the region (Ranasinghe *et al.*, 2021). It is projected that the number of days exceeding 35 °C of high heat stress will increase by more than 60 days in parts of the region by the mid-21st century under SSP5-8.5 (Ranasinghe *et al.*, 2021). At the end of the century, the number of days exceeding dangerous heat stress thresholds (i.e., days with a heat index of more than 41 °C) is projected to increase by 100 days in some areas of Southeast Asia under SSP1-2.6 and by about 250 days under SSP5-8.5 at the end of the century (see Figure 12.4 in Ranasinghe *et al.*, 2021). Zhu *et al.* (2020) found that temperature extreme changes are over densely populated coastal regions in Southeast Asia.

Recent projections from CMIP6 models indicate a future increase in the intensity and frequency of heavy precipitation in Southeast Asia with *medium confidence* under a 1.5 °C GWL, relative to the 1995–2014 period, and with increasing confidence in the intensification of heavy precipitation at a higher GWL (Table 11.8 in Seneviratne *et al.*, 2021). Flooding and landslides are projected to increase in the region as a consequence of more intense heavy precipitation as well as changes in land use (Ranasinghe *et al.*, 2021). On the other hand, there is *low confidence* in future trends in agricultural and ecological drought, and hydrological drought across GWLs due to inconsistent trends or limited evidence (Table 11.9 in Seneviratne *et al.*, 2021). TCs affecting Southeast Asia are projected to decrease in frequency, but there is *medium confidence* that the frequency of intense TCs will increase (Ranasinghe *et al.*, 2021).

Apart from the RSLR, there is *high confidence* in the projected increase in magnitude and frequency of ETWL in Asia. In Southeast Asia, the present-day 1-in-100-year ETWL is projected to occur at least annually, both by the mid- and end of the 21st century (Ranasinghe *et al.*, 2021). Also, MHWs are projected to be more intense and of longer duration in coastal regions of Southeast Asia (Ranasinghe *et al.*, 2021).

Table 2.5 summarizes the direction of future changes, including confidence assessment, in CIDs that are broadly relevant for Southeast Asia.

2.4 Research Gaps and Recommendations for Future Research

This chapter discussed the observed and projected changes in the global climate system, highlighting the changes in CIDs that are broadly relevant in Southeast Asia. However, there are still several CIDs with *low confidence* in the direction of observed and projected changes, as well as in the human attribution, such as drought (meteorological, hydrological, agricultural, and ecological), fire weather, mean winds, severe wind storm, among others, even though there has been notable progress in observational data analysis and climate downscaling activities in Southeast Asia (Tangang *et al.,* 2021). Hence, further examination of these CIDs, especially considering their relevance and impacts on various systems and sectors, presents potential directions for research in the region.

Table 2.5

Regional summary of future changes in climatic impact-drivers (CIDs) that are broadly relevant for Southeast Asia

CID		FUTURE CHANGES
Heat and Cold	Mean air temperature	▲ Increase (*high confidence*)
	Extreme heat	▲ Increase (*high confidence*)
	Cold spell	▼ Decrease (*high confidence*)
Wet and Dry	Mean precipitation	▲ Increase* (*medium confidence*)
	River flood	▲ Increase (*medium confidence*)
	Heavy precipitation and pluvial flood	▲ Increase (*high confidence*)
	Landslide	▲ Increase (*medium confidence*)
	Aridity	(*low confidence* in direction of change)
	Hydrological drought	(*low confidence* in direction of change)
	Agricultural and ecological drought	(*low confidence* in direction of change)
	Fire weather	(*low confidence* in direction of change)
Wind	Mean wind speed	(*low confidence* in direction of change)
	Severe wind storm	(*low confidence* in direction of change)
	Tropical cyclone	▲ Increase** (*medium confidence*)
	Sand and dust storm	(*low confidence* in direction of change)
Snow and Ice	Hail	(*low confidence* in direction of change)
Coastal and Oceanic	Relative sea level	▲ Increase (*high confidence*)
	Coastal flood	▲ Increase (*high confidence*)
	Coastal erosion	▲ Increase*** (*high confidence*)
	Marine heatwave	▲ Increase (*high confidence*)
	Ocean and lake acidity	▲ Increase (*high confidence*)
Other	Air pollution weather	(*low confidence* in direction of change)
	Atmospheric CO_2 at surface	▲ Increase (*high confidence*)
	Radiation at surface	(*low confidence* in direction of change)

* *High confidence* in decrease in precipitation in Indonesia

** Tropical cyclones increase in intensity but decrease in number

*** Increase in coastal erosion along sandy coasts and in the absence of additional sediment sinks or sources or any physical barriers to shoreline retreat. Substantial parts of the coasts in this region are projected to prograde if present-day ambient shoreline change rates continue

SOURCES: ADAPTED FROM TABLE 12.4 IN RANASINGHE *et al.* (2021), TABLE TS.5 IN ARIAS *et al.* (2021), AND IPCC WG1 INTERACTIVE ATLAS: REGIONAL SYNTHESIS (GUTIÉRREZ *et al.*, 2021B; ITURBIDE *et al.*, 2021)

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Observed Changes in the Philippine Climate

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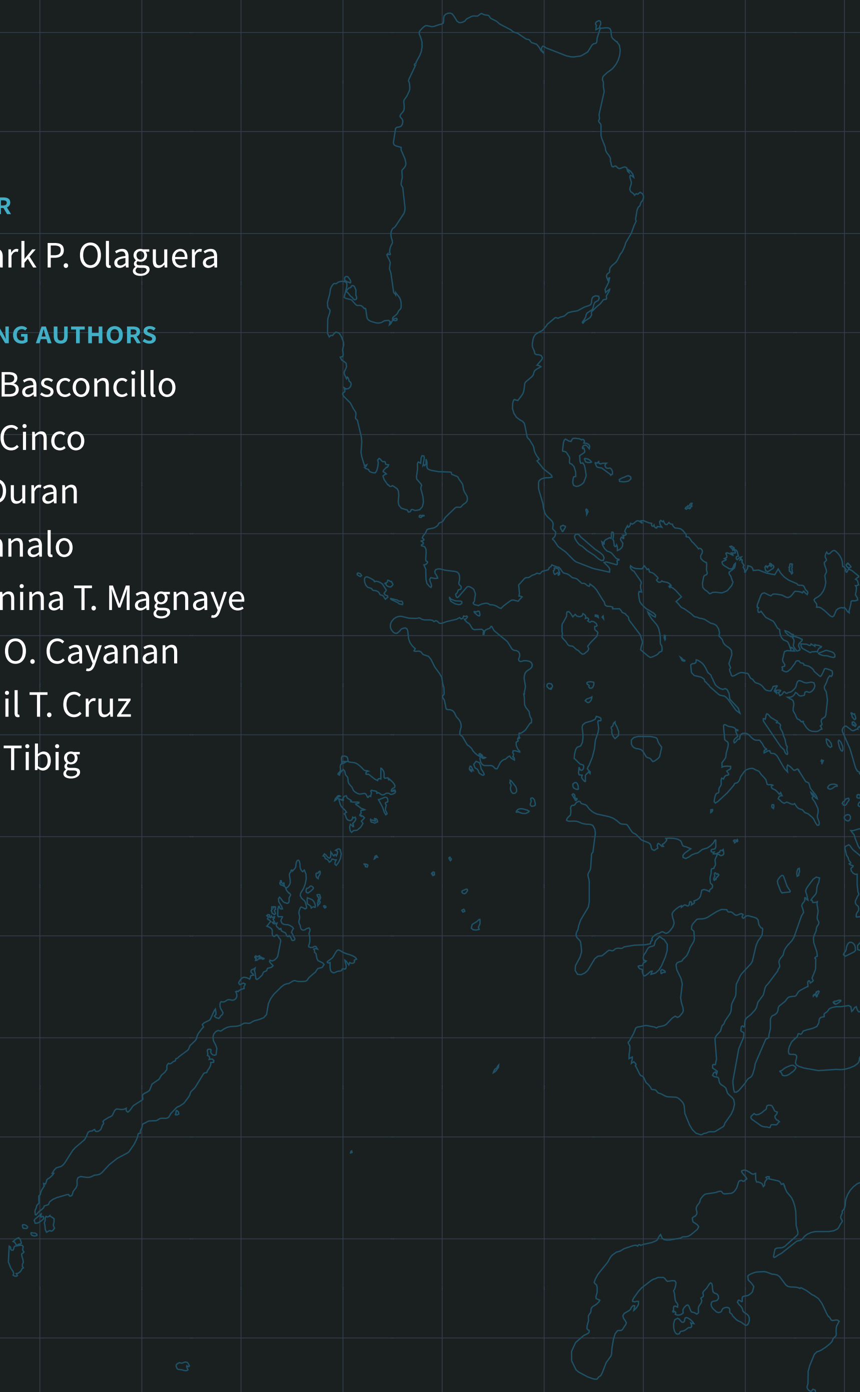
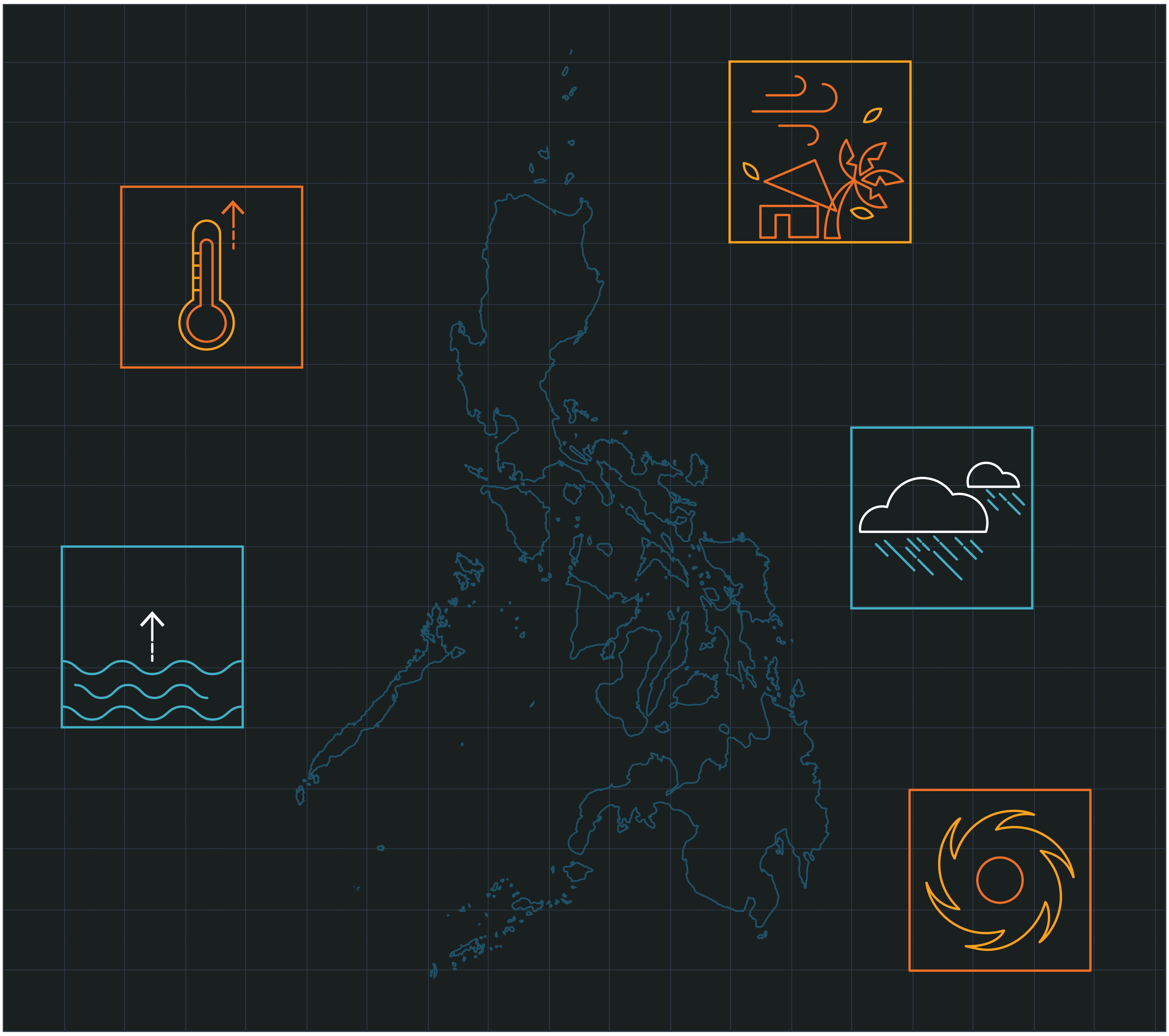




3.1 Chapter Summary

The climate of the Philippines is complex. The heterogenous topography and many atmospheric systems, such as tropical cyclones (TCs), shearlines, southwest (*Habagat*) and northeast (*Amihan*) monsoons, and intraseasonal oscillations (ISOs), including the interactions among these systems, contribute to its complexity. Elucidating the mechanisms and dynamics of these atmospheric systems and their interactions is key to understanding the impacts of climate change on the country. This chapter describes the recent literature on the observed changes in the climate of the Philippines (***Figure 3.1***) since the publication of the first Philippine Climate Change Assessment (PhilCCA) Report.

A recent countrywide analysis of annual mean temperature in the Philippines revealed an overall increasing trend of about 0.16 °C per decade from 1951–2018, with higher and more significant trends observed in the nighttime temperature than the daytime temperature, particularly during the December to February (DJF) season. The urbanization effect on temperature trends was also quantified by classifying the stations into urban and rural stations using satellite night lights and showed a larger and more significant urbanization contribution and effect in temperature indices related to Tmin compared to those related to Tmax.

Rainfall over the Philippines is influenced by different atmospheric processes such as wind systems and high-pressure areas with different spatial and temporal scales. For example, during the *Habagat* and *Amihan* seasons, rainfall is influenced by the Western North Pacific Subtropical High (WNPSH). This high-pressure system was found to affect the onset of the *Habagat* season, the occurrence of monsoon breaks over Luzon Island, and, in general, the tracks of TCs. Some climate shifts related to the phase change of the Pacific Decadal Oscillation (PDO) were identified during the 1993–1994 *Habagat* season and then the 1976–1977 and 1992–1993 *Amihan* seasons.

More studies have been done in particular locations to better understand the factors that contribute to rainfall variability, such as winds, sea surface temperature (SST) over the West Philippine Sea, topography, and land cover. A significant increase in rainfall over Metro Manila by about 78 mm per decade from 1901–2018 was found. Some extreme rainfall events over Metro Manila from 1901–2018 were identified and associated with TCs or their interaction with the southwesterlies during the *Habagat* season. Moreover, a recent numerical study revealed that urbanization can potentially enhance rainfall associated with the *Habagat* over Metro Manila by 20%.

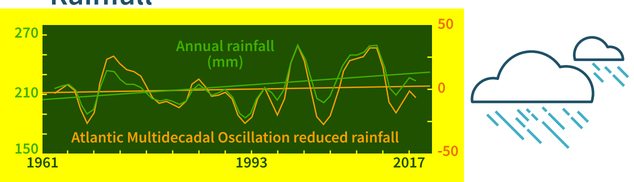
The cost of damages associated with TCs is significantly increasing, which is consistent with the PhilCCA 2016. While the annual frequency and intensity of TCs in the Philippines show no discernible long-term trend, the number of Christmas typhoons has significantly increased by 210% since 2012. However, there is limited report on the variability and trend of the other TC metrics (e.g., duration, speed, and others). Previous reports also demonstrate that the temporal analysis of TC climatology is *likely* sensitive to the reliability of best track data. Hence, it remains critical to revisit such reported long-term trends in view of the identified reliable TC period as applied to the Philippine context. Moreover, there is also a significant increase in TC-induced rainfall in the Philippines. Since 2000, the TC rain percentage contribution has increased by 16.9%–19.3% per decade. From 1958–2017, there was a significant increase of 6.0% per decade in the mean annual number of high precipitation event (HPE) days and 12.7% per decade in the annual total HPE precipitation, both of which are primarily due to TCs. The contribution of non-TC vortices (i.e., weaker disturbances than TCs) to the rainfall variability of the Philippines has also been recently quantified from 1979–2020. These non-TC vortices were found to occur more frequently during the DJF season and have the highest contribution to the mean daily rainfall (80%–90%) in northeast Mindanao. However, the trends of their rainfall contribution have not been assessed.

There is limited literature on the observed trends in sea level change across the country. Previous studies using satellite datasets found that the sea level has risen

Figure 3.1

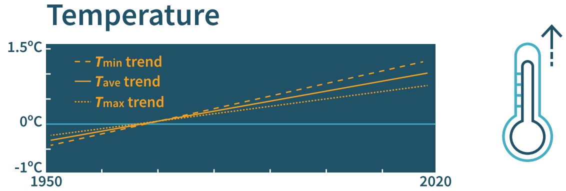
Observed changes and extreme events in the Philippine climate

Rainfall



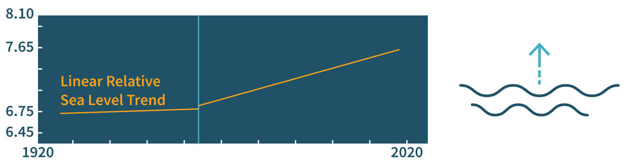
No increasing trend in the mean annual rainfall but a significant shift around 1994/1995 has been detected. Wetter condition during 1995-2020 period

Temperature



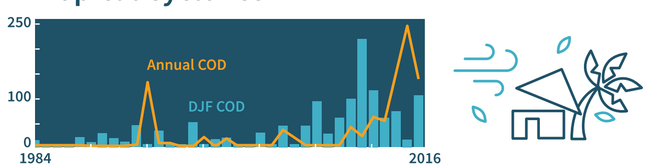
Increasing trend of about 0.16°C per decade from 1951–2018, with higher and more significant trends observed in the nighttime temperature particularly during the DJF season

Sea Level Rise



Sea level rise by as much as 4.5-5 mm per year was also observed in some parts of the country including east of Samar, Leyte, and regions along the southwestern coasts of the Central and Western Visayas, and east of Mindanao and south Zamboanga

Tropical Cyclones



The cost of damages (COD) associated with TCs is significantly increasing. While the annual frequency and intensity of TCs in the Philippines show no discernible long-term trend, the number of Christmas typhoons has significantly increased by 210% since 2012.

SOURCES: BASCOCILLO *et al.* (2023), MANALO *et al.* (2002), PERMANENT SERVICE FOR MEAN SEA LEVEL (2022), AND BASCONCILLO & MOON (2021).

by about 5–7 mm per year over the Philippine Sea from 1993–2015. Sea level rise by as much as 4.5–5 mm per year was also observed in some parts of the country, including the east of Samar, Leyte, and regions along the southwestern coasts of the Central and Western Visayas, and the east of Mindanao and south Zamboanga. This large increase in sea level has been suggested to be partly due to natural modes of ocean variability, such as El Niño Southern Oscillation (ENSO) and PDO, and partly due to an anthropogenic signal.

This chapter noted some of the research gaps that should be addressed in the future, such as (1) the factors that contribute to the spatiotemporal variability of temperature, which is less examined compared to rainfall; (2) the possible role of anthropogenic aerosols on the increasing trend of temperature; (3) the climatology, long-term trend, and variability of surface winds, extreme cases of which may potentially lead to damages to infrastructure and loss of human lives; (4) countrywide estimation of local sea level rise; and (5) limited studies on TC dynamics and variability. The lack of long-term and homogenous datasets remains the biggest challenge in characterizing the observed changes in the Philippine climate, particularly for surface winds and sea level rise.

3.2 Introduction

PhilCCA 2016 noted some of the research gaps on the different local drivers contributing to climate variability in the country. This notwithstanding, the following observed changes in the Philippine climate were noted:

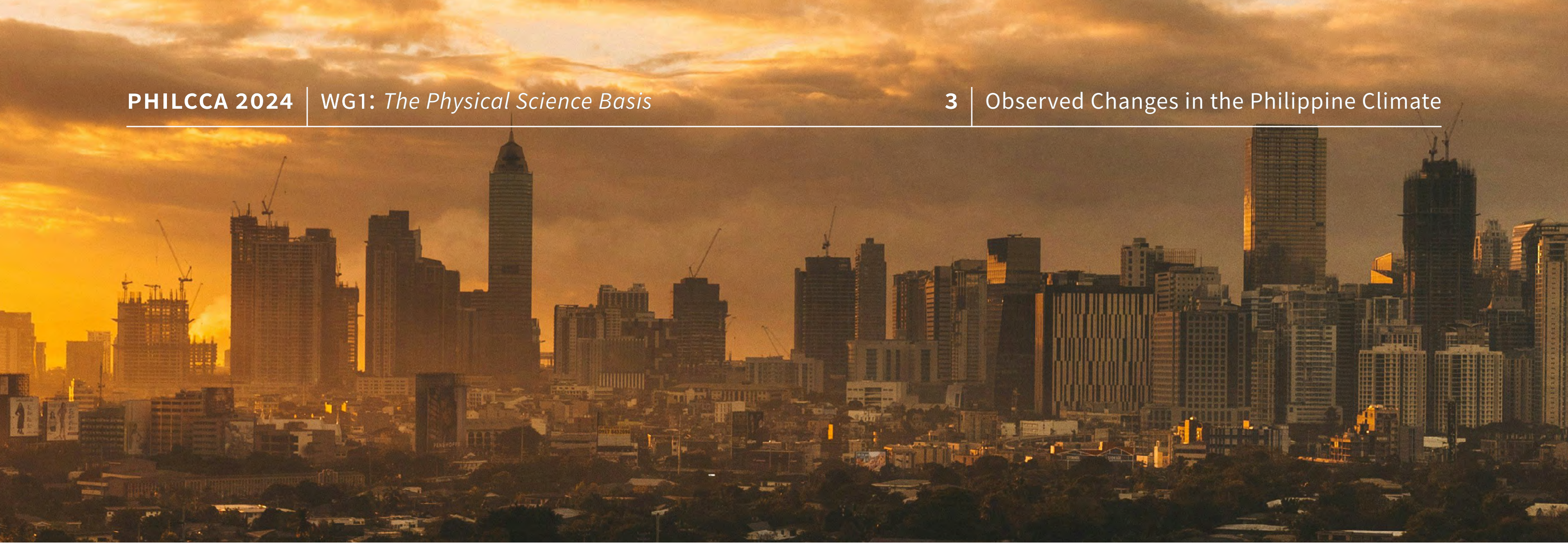
A There is consensus on the increasing trends in surface temperature or the occurrence of more warm nights over the country based on previous literature. Specifically, an increase of 0.65 °C, 0.36 °C, and 1 °C has been observed for the annual mean temperature, mean annual maximum, and minimum temperatures, respectively, during the period 1956–2010. The change in the minimum temperature is more pronounced, indicating more numerous warmer nights in the country.

B Unlike the trends in temperature, there is higher spatiotemporal variability in the trends in rainfall. For example, Cruz *et al.* (2013) found decreasing trends in the southwest monsoon rainfall over the western coast station in the country during the period 1961–2010, but earlier studies such as Jose *et al.* (1996) found increasing trends in the seasonal and total rainfall during 1952–1992. A study by Cinco *et al.* (2014) showed increasing trends in the extreme daily rainfall intensity in most parts of the country during the period 1951–2008.

C Trends in TC activity were also examined. The study by Cinco *et al.* (2016) showed no significant trends in the annual number of TCs that entered the Philippine Area of Responsibility (PAR) from 1951–2013, but the damage costs associated with TCs have been increasing. A slightly decreasing trend in the number of landfalling TCs in the last two decades was also noted in their study.

A number of studies have reevaluated the trends in rainfall, temperature, and TCs since the publication of PhilCCA 2016 using longer and homogenized datasets. Some of the research gaps noted in the previous report, such as the decadal variability in rainfall and TCs and sea level change around the country, were examined in more recent studies, which will be discussed in the following subsections.

The rest of the report is organized as follows: Section 3 discusses the recent observational and numerical modeling studies on temperature variability, extremes, and trends across the country. The contribution of urbanization to temperature trends is discussed as well. The observed trends in the seasonal, annual, and extreme rainfall events as well as changes in the monsoon patterns are discussed in Section 4. The variability of TC activity, including trends in TC frequency and associated damage costs, is discussed in Section 5, while recent research and trends on sea level rise are discussed in Section 6. Some of the issues that still need to be addressed in future studies are presented in Section 7.



3.3 Temperature

Recent observational studies indicate a substantial decrease in the number of cold days and nights and an increase in the number of warm days and nights around the world since the 1950s. There is also consensus among regional and global climate model simulations on the projected increase in temperature in the near and far future should greenhouse gas emissions continue to rise. These changes in temperature have profound impacts on agriculture and human society. As such, understanding its variability and the associated mechanisms is necessary.

Previous studies focused on assessing the seasonal or annual trends in surface temperature (e.g., Masud *et al.*, 2016; Villafuerte *et al.*, 2020) and relating these changes to climate change. It is known that both anthropogenic forcing and urbanization contribute to the increasing temperature trends around the world (e.g., Sun *et al.*, 2019; Zhao *et al.*, 2019). Sun *et al.* (2019), for example, demonstrated that the impact of anthropogenic forcing in eastern China on the observed changes in temperature is more apparent during the daytime, whereas the impact of urbanization is more apparent during the night. Urban expansion alters the land cover and consequently affects the radiation and energy balance in these areas. The materials used in urban areas favor heat retention, leading to warmer temperatures than their surrounding rural counterparts. With the aid of numerical model simulations, Dado and Narisma (2019) and Oliveros *et al.* (2019) showed that urbanization is one of the key contributors to the observed increase in the near-surface temperature in Metro Manila.

The variability of temperature appears to have been less examined in previous studies. Estoque *et al.* (2020) assessed the heat health risk in major cities in the Philippines using satellite-based surface temperatures and found that those cities located within Metro Manila have higher exposure to heat-related hazards. In 2018, the Department of Science and Technology-Philippine Atmospheric, Geophysical and Astronomical Services Administration (DOST-PAGASA) released a report on the observed and projected climate change in the Philippines. This is supplemented by a recently published climate extremes report by DOST-PAGASA, Manila Observatory (MO), and Ateneo de Manila University (ADMU) (2020). The following subsections summarize the recent observed changes in temperature in the Philippines.

3.3.1 Changes in extremes

Extreme indices, such as those defi ned by the Expert Team on Climate Change Detection and Indices, are usually used to characterize extreme temperatures in terms of intensity, frequency, and duration. Such indices, including those in some studies (Cinco *et al.*, 2016), have been revised and utilized in recent analysis conducted within the country for both regional and countywide scale analysis (Bagtasa, 2019; Manalo *et al.*, 2021). For example, Bagtasa (2019) examined the trends in daily minimum (Tmin) and maximum temperature (Tmax) over Metro Manila using observation data from 1901–2018. He found increasing trends in the monthly maximum (0.012 °C/decade) and monthly minimum (0.38 °C/decade) temperatures. The diurnal temperature range (DTR) was also found to be decreasing at a rate of 0.021 °C per decade. The frequency of warm (or cold) nights has been increasing (or decreasing).

A countrywide analysis of changes in extreme temperature was conducted by Manalo *et al.* (2021), and their results are summarized in ***Table 3.1***. Generally, higher and more significant trends were observed in indices related to Tmin such as the maximum value of Tmin (TNx), minimum value of Tmin (TNn), percentage of days when Tmin is less than the 10th percentile (TN10p), and percentage of days when Tmin is greater than the 90th percentile (TN90p), compared to indices related to Tmax such as the maximum value of Tmax (TXxx), percentage of days when Tmax is less than the 10th percentile (TX10p), and percentage of days when Tmax is greater than the 90th percentile (TX90p). Their results are consistent with other local (Metro Manila; Bagtasa, 2019), regional (Southeast Asia;

Cheong *et al.*, 2018), and global (Zhang *et al.*, 2021) studies on temperature trends. In addition, their seasonal analyses show that most of the indices have higher trends during the DJF and March to May (MAM) seasons compared to the other seasons. The highest trend was observed for TN10p during the DJF season with a trend equivalent to −3.58%/decade, while the lowest trend was observed for DTR during the September to November (SON) season with a trend of −0.021 °C/decade. The large decreasing trend observed in indices related to cool nights is partly related to the urban heat island (UHI) effect (Oke *et al.*, 2017; Zhang *et al.*, 2021). On the other hand, lower trends were observed in the June to August (JJA) and SON seasons, which corroborates an earlier global study by Easterling (1997).

3.3.2 *Trends in the Mean Annual and Seasonal Temperature*

The annual mean temperature, maximum, and minimum temperature in the Philippines were found to be increasing at an average rate of 0.10 °C/decade, 0.05 °C/decade, and 0.15 °C/decade, respectively, from 1951–2015 (PAGASA, 2018). These trends were recently reevaluated by Manalo *et al.* (2021) using only the stations and years with less than 20% missing data (<72 days of missing data) and a longer dataset from 1951–2018. The trends for the annual mean, maximum, and minimum temperatures are 0.16 °C/decade, 0.14 °C/decade, and 0.17 °C/decade, respectively. Moreover, a similar report by Basconcillo *et al.* (2023) found a signifi cantly decreasing trend in the annual DTR in the Philippines from 1961–2020. This implies that the diff erence in daytime and nighttime temperatures is becoming smaller, which, in turn, may prompt changes in the existing diurnal processes (e.g., land breeze and sea breeze, natural circadian rhythm, and others). The observed trends in minimum and average temperature in Metro Manila are comparable to countrywide trends; generally, there are fewer cold nights and more warm days (Bagtasa, 2019). A decreasing Tmax trend from 1992–1996, which is evident in both Metro Manila and countrywide data, was also observed. Such a cooling eff ect may be attributed to the Mount Pinatubo eruption in Central Luzon in 1991, whose effect persisted in the following years (Bagtasa, 2019; Manalo *et al.*, 2021).

Table 3.1

Annual and seasonal trends of the temperature indices in the Philippines from 1951–2018

	ANNUAL	DJF	MAM	JJA	SON
Tave	0.17***	0.17***	0.17***	0.16***	0.17***
Tmin	0.19***	0.18***	0.19***	0.18***	0.18***
Tmax	0.15***	0.15***	0.15*	0.14**	0.16***
DTR	-0.04*	-0.04	-0.04	-0.04*	-0.02
TNn	0.20***	0.23***	0.24***	0.16***	0.22***
TNx	0.19***	0.17***	0.16*	0.14***	0.12***
TXn	0.16***	0.19***	0.13***	0.16***	0.20***
TXx	0.14***	0.15***	0.15***	0.16***	0.16***
TN10p	-1.98***	-3.58***	-1.58***	-0.95***	-1.49***
TN90p	2.46***	0.75***	3.29***	3.40***	1.98***
TX10p	-0.94***	-1.98***	-0.26*	-0.66***	-0.91***
TX90p	1.58***	0.42***	2.63***	2.07***	1.22***
Hottest days	0.20***	-	-	-	-
Coldest nights	-0.21***	-	-	-	-

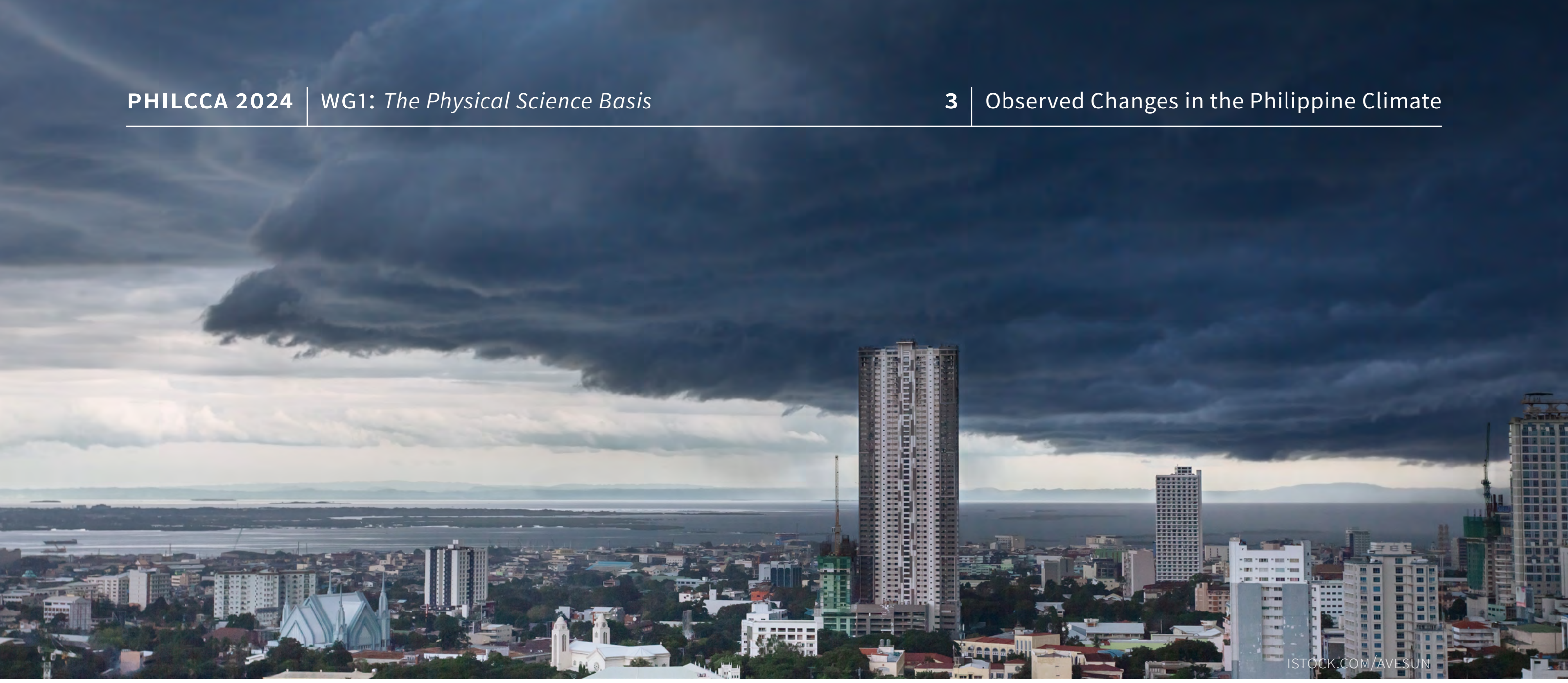
* significant at α = 0.05
** significant at α = 0.01
*** significant at α = 0.001
Italicized: decreasing trend
SOURCE: ADAPTED FROM MANALO *et al.* (2021)

3.3.3 *Impact of Urbanization on Temperature Indices*

Classifying the DOST-PAGASA stations into urban and rural is crucial when assessing the influence of urbanization on temperature trends. Manalo *et al.* (2021) used satellite night lights to determine the percentage of urban grid points within a 12-km radius surrounding the DOST-PAGASA stations. Urban grid points are those grid points whose digital numbers (units of satellite night lights) exceed 25.5. A station is classified as a rural station when the total number of urban grid points surrounding that station is less than 33%. The trends of the annual and seasonal indices for both Tmin and Tmax were computed. The urbanization effect on the trends of temperature indices can be expressed as the difference between the trends of the indices of the urban and rural stations (i.e., Turban minus Trural). In other words, the impact of urbanization on temperature trends is manifested by the change in UHI intensity.

The annual analysis of the urbanization effect by Manalo *et al.* (2021) shows that the trends of the urbanization effect on temperature indices are all significant at the 95% confidence level except for some indices related to maximum Temperature (Tmax), such as Tmax, maximum value of Tmax (TXx), percentage of days when Tmax is less than the 10th percentile (TX10p), and percentage of days when Tmax is greater than the 99th percentile (hottest day). This effect was larger and more significant in the indices of minimum temperature (Tmin), DTR, TNn, TNx, percentage of days when Tmax is greater than the 90th percentile (TX90p), TN10p, TN90p, and percentage of days when Tmin is less than the 1st percentile (coldest nights), with absolute values of 0.10 °C, 0.11 °C, 0.13 °C, 0.09 °C, 0.52%, 0.84%, 1.19%, and 0.10% /decade, respectively. On the other hand, lower and insignificant trends of urbanization effect were observed in indices of minimum value of Tmax (TXn), TXx, TX10p, and percentage of days when Tmax is greater than the 99th percentile (hottest days). The urbanization contribution, which is defined as the proportion of statistically significant urbanization effects, was also calculated (ranging from 20%–90%) and showed that a higher and more significant urbanization contribution was observed in Tmin, DTR, TNn, TNx, TX90p, TN90p, and the coldest nights. This means that urbanization has a greater effect on nighttime temperatures than on daytime temperatures. These findings are consistent with the analysis conducted by Shen *et al.* (2020) for northeast China from 1960–2016, where they observed a more significant urbanization effect for indices related to Tmin compared to those related to Tmax. In terms of seasonal analysis, urbanization was observed to have a higher effect on most temperature indices during the DJF season. As mentioned by Oke *et al.* (2017), such magnitudes critically depend on moisture content measured in rural stations due to its greater seasonal variation. Based on the Japan Meteorological Agency's (JRA) JRA-55 atlas, the total moisture is smaller in DJF compared to the other seasons in the country (http://jra.kishou.go.jp/JRA-55/atlas/en). This might also be due to a possibly lower and more stable urban boundary layer due to lower temperatures observed during DJF compared to other seasons (Villafuerte *et al.*, 2020).

A number of studies have also examined the trends in temperature in major cities in the Philippines, where the impact of urbanization is more pronounced. For example, Landicho and Blanco (2019) used remote sensing (multi-temporal Landsat data from 1997–2019) to characterize the trend and detect intra-UHI in Metro Manila. They observed an annual increase in temperature of about 0.18 °C during their study period. They also observed an extension in the hot spot areas (around 0.03 km^2; particularly in the cities of Caloocan, Manila, Pasay, and Quezon) and a decrease in the cold spot areas (around 0.03 km^2; particularly in the cities of Caloocan, Las Piñas, Malabon, Navotas, and Valenzuela). A cloud computing tool (Climate Engine) was used by Rejuso *et al.* (2019) to analyze the spatiotemporal characteristics of UHI in Mandaue City, Philippines. The time series analysis was conducted to determine the impacts of increased built-up area and decreased vegetation cover on surface temperature from 2013–2019. They were able to identify the specific barangays with hot spots, which are Tipolo (100%), Bakilid (100%), Ibabao-Estancia (93.5%), Alang-Alang (87.2%), Guizo (84.4%), Subangdaku (84.1%), and Centro (79.4%). Furthermore, areas with vegetation considered cold spots were also detected (barangays Casili and Tawason, with 100% and 52%, respectively).



3.4 Rainfall

In recent years, the seasonal and diurnal rainfall variability in the Philippines has been studied, covering a wide range of spatiotemporal scales. The Cordillera Mountains to the west and the Sierra Madre Mountains to the east of Luzon Island induce monsoon-blocking effects, such that the areas along the west (east) coast receive higher rainfall amounts during the *Habagat* (*Amihan*) season than areas along the east (west) coast. The areas along the east coast generally receive higher rainfall amounts annually than the west coast because of TCs and other rainfall-producing disturbances in addition to the rainfall brought by the monsoon systems. The importance of Luzon island's topography on the diurnal cycle of rainfall was examined by high-resolution numerical simulations by Riley-Dellaripa *et al.* (2020) and on the intensity and distribution of rainfall associated with landfalling TCs by Racoma *et al.* (2016, 2023). The spatial contrast in rainfall patterns induced by the complex topography of the country is well documented, but it is only recently that some of the important processes during *Habagat* and *Amihan* seasons have been elucidated (Akasaka *et al.*, 2018; Bagtasa, 2021; Bañares *et al.*, 2021; Chudler *et al.*, 2020; Kubota *et al.*, 2017; Matsumoto *et al.*, 2020; Natoli & Maloney, 2019, 2021; Olaguera *et al.*, 2021a,b,c, 2018a,b, 2022, 2023a,b; Riley Dellaripa *et al.*, 2020).

The *Habagat* (*Amihan*) season starts around late May (late October) and withdraws around mid to late September (March) over the western (eastern) portion of the Philippines, while the dry season is influenced by the position and intensity of the WNPSH, particularly from MAM (Akasaka *et al.*, 2018). Aside from the seasonal rains, the diurnal cycle of rainfall over the Philippines is another important mode of rainfall variability. Previous studies found that the diurnal amplitude over Mindanao Island is in phase with daily mean precipitation but is almost out of phase over Luzon Island (Natoli & Maloney, 2019). Furthermore, Lee *et al.* (2021) found that the diurnal cycle of rainfall over Luzon from MAM shows an eastward propagation tendency, which is opposite to the direction of the large-scale easterly winds in this season. They suggested that this is attributable to the local circulation features such as the mountain–valley breeze, the land–sea breeze, and their interaction with the Sierra Madre mountain range.

Over Metro Manila, local rainfall events usually occur in the afternoon during the *Habagat* season, during which convective events move along the prevailing southwesterly winds (Bañares *et al.*, 2021). The northern and central areas of Metro Manila receive an annual total rainfall of more than 2,500 mm, while the southern areas receive around 2,000 mm of total rainfall. About 25% of the total rainfall received over Metro Manila during the *Habagat* season is induced directly and indirectly by TCs, while about 70% of the total rainfall comes from stratiform rain clouds during the *Amihan* season.

PhilCCA 2016 Working Group 1, particularly Chapter 4, noted a decreasing trend in mean rainfall during the *Habagat* season (Cruz *et al.*, 2013) from 1961–2010 over the northwest Philippines. The response of rainfall to ENSO during July to September is reversed compared with October to December (Lyon *et al.*, 2006; Villarin *et al.*, 2016). In terms of extreme rainfall, interannual variability using several indices is also influenced by ENSO, with El Niño (La Niña) events leading to drier (wetter) conditions over the Philippines (Villafuerte II *et al.*, 2014). In rainfall-related events such as floods, Hilario *et al.* (2009) studied major drought events that happened during the 1980s and 1990s. These outdated findings highlight the need to update recent findings on rainfall trends, changes, and patterns that are covered in this section.

3.4.1 *Trends and Changes in Annual and Seasonal Rainfall*

In contrast to the trends in temperature, there is no notable trend in the mean annual rainfall in the Philippines from 1961–2020; however, a positive regime shift was detected from 1995–2020 (Basconcillo *et al.*, 2023). Such an abrupt increase in the mean annual rainfall was attributed to the enhanced Pacific Walker circulation, which was driven by the transition of the Atlantic Multidecadal Oscillation (AMO) to its positive phase since the mid-1990s. Moreover, a significantly increasing trend in the boreal winter rainfall (i.e., December to January) was observed in the Philippines from 1961–2020 (Basconcillo *et al.*, 2023). Such trends imply that the Philippines has become wetter in recent decades.

Consistent with the previous report, Akasaka *et al.* (2018) found three changes in the observed rainfall patterns since the 1990s: (1) prolonged peak rainfall with minimal dry season from January to March; (2) dry season with a shorter rain period during the *Habagat* season; and (3) dry season and delayed onset and withdrawal of the *Habagat*. The first pattern had an early onset of *Habagat*, and the longer duration of peak rainfall can be related to the early and strong westerly winds. The clear dry seasons from February to March related to the latter two patterns were found to be connected to the strength and location of the WNPSH. Changes in the atmospheric conditions at lower pressure levels suggest an increase in rainfall since the latter part of the 1990s. Furthermore, the seasonality of the *Habagat* season was characterized by the occurrence of ENSO, suggesting that long-term changes in rainfall during the *Habagat* season may be influenced by this climate phenomenon.

There is a climatological increase in rainfall before the onset of *Habagat* by at least two pentads (i.e., 10-day intervals) due to TCs and other synoptic disturbances in some years (Matsumoto *et al.*, 2020). Moreover, at the onset of *Habagat*, the climatological rainfall over the western parts of the Philippines increases from June to October (Kubota *et al.*, 2017). TCs were also found to possibly induce the early onset of the *Habagat* season by enhancing the moist southwesterly winds. The rainfall over the east Philippines associated with the *Amihan* increases from October to March. It was further noted that the rainfall change in this season starts first over the northern Philippines and then moves southward (Kubota *et al.*, 2017).

In Metro Manila, the total annual precipitation was found to increase by about 78 mm/decade based on a blended dataset from 1901–2018 (Bagtasa, 2019). The increase in the number of wet days was suggested to contribute to the increase in total rainfall in the metropolis. TCs are highlighted as one of the main factors in the anomalously high total annual rainfall, thus increasing the number of wet days in Metro Manila. However, ENSO was found not to be correlated with Metro Manila rainfall variability.

3.4.2 *Changes in the Monsoon Patterns*

Rainfall variability in the western Philippines is mainly influenced by the *Habagat*. Warmer (or cooler) SSTs that are related to weaker and stronger cooling have been linked to less (or more) rainfall over the western Philippines (Takahashi & Dado, 2018). The onset of the *Habagat* appears to have started earlier in May, after the mid-1990s. This is confirmed by in situ data over the West Philippine Sea showing prevailing westerly winds in May after the mid-1990s (Kubota *et al.*, 2017).

Olaguera *et al.* (2021a) investigated the evolution of the onset of the *Habagat* season. Three abrupt phases were identified: (1) the monsoon onset phase happening between mid to late May and with increased rainfall along the western coastal area of Luzon Island; (2) the monsoon break phase, occurring after onset by early June and with the westward extension of the WNPSH, decreasing southwesterly winds and reduced convection in Luzon island; and (3) the monsoon revival phase, characterized by northward movement of the WNPSH, enhancement of southwesterly winds, and rainfall. Matsumoto *et al.* (2020) used pentad analysis to determine the evolution of the *Habagat* season. The onset of the *Habagat* starts earlier in northern Luzon compared to the southern areas. The north-eastward movement of the *Habagat* first happens from about late May to July, with a monsoon trough feature. Then, the *Habagat* fully weakens by late September, when the southwesterly winds decline and easterly winds dominate over the Philippines. The evolution of the monsoon, from onset to retreat, is shown to be influenced by synoptic scale disturbances. Olaguera *et al.* (2023a) recently investigated the climatology of monsoon breaks in June to September from 1979–2020. A monsoon break is defined as a period when the average rainfall across the eight Type 1 stations along the west coast of Luzon decreases by 5 mm/day for at least three consecutive days. They found that the majority (about 63%) of the monsoon breaks are short-duration breaks, lasting about 3–4 days. The occurrence of monsoon breaks was found to be modulated by the 30- to 60-day mode of the Boreal Summer Intraseasonal Oscillation (BSISO), with more breaks occurring in Phases 1–4 of the BSISO. In these phases, an anomalous anticyclone associated with the BSISO appears in the vicinity of the Philippines, which favors the westward extension of the WNPSH, leading to more monsoon breaks.

Climate shifts also occur in different seasons. During 1993–1994, from August to September, an abrupt climate shift was detected when the suppressed rainy season during 1994–2008 was compared with the 1979–1993 climate (Olaguera *et al.*, 2018a). Because the WNPSH moved westward in the latter time slice, the low-level divergence strengthened and reduced moisture supply over the Philippines. However, a recent recovery on the said rainfall decrease was detected from 1991–2020, where a significantly increasing trend in the boreal summer rainfall (i.e., JJA) was observed only for stations located in the western section of the country (Basconcillo *et al.*, 2023). Meanwhile, two interdecadal shifts were identified in December around 1976–1977 and 1992–1993 based on the monthly analysis done from 1961–2008 rainfall data in the Philippines (Olaguera *et al.*, 2018b). The first interdecadal shift was associated with the shifting of the PDO from its negative to positive phase, a change in SST over the Pacific basin similar to modulation during El Niño. On the other hand, the 1992–1993 interdecadal shift was associated with the SST change in the Pacific basin, similar to La Niña. A decrease in the mean rainfall after this shift was attributed to the observed decrease in TC activity, a decrease in moisture transport, and slower low-level easterly winds.

Urbanization can also enhance rainfall associated with the *Habagat* over Metro Manila by 20% (Dado & Narisma, 2019). The previous numerical study compared an expanded urban cover in 2001 versus 1972 in Metro Manila. The study also noted that updating the land cover with urban expansion in the simulation captured the observed rainfall increase. They suggested that urban expansion increases surface temperature and surface roughness, which favors an increase in vertical wind speeds and turbulent energy. These changes eventually lead to an increase in convective activity and rainfall.

3.4.3 Trends and Changes in Extreme Rainfall Indices

Extreme rainfall can be measured in a variety of ways, such as its intensity (how much rain), frequency (how often), duration (how long), and the like. According to the Philippine Climate Extremes Report 2020 (DOST-PAGASA, MO, & ADMU, 2021), the average rainfall intensity ranges from 5 to 21 mm/day, with high amounts observed over western Luzon and northwestern Mindanao. The maximum 1-day rainfall (Rx1day) associated with monsoons, TCs, and local thunderstorms is ~180 mm in northern, southern, and southeastern Luzon, eastern Visayas, and Mindanao. Western Mindanao has a Rx1day of 30 mm. Over western and southern Luzon, eastern Visayas, and northeastern Mindanao, ~380 mm of total maximum 5-day rainfall (Rx5day) has been experienced historically. The maximum rainfall during very wet days (P95; days exceeding the 95th percentile) ranges from 15 to 60 mm. Very wet days with 60 mm are typically experienced over western, southern, and southeastern Luzon, eastern Visayas, and Mindanao, while 15 mm are experienced over southwestern Mindanao. Extremely wet days (P99; days exceeding the 99th percentile) with a maximum rainfall of 160 mm/day are typically experienced over eastern Mindanao and a minimum amount of 20 mm/day over western Mindanao.

The number of very wet days ranges from 5–12 days (P95d), while the number of extremely wet days is about 1–2 days (P99d) over the Philippines. The total rainfall during extremely wet days (R99p) is up to 300 mm, mostly over the eastern Philippines. The archipelago has at least eight consecutive wet days (at least 1 mm), while the southern Luzon and Visayas regions experience continuous rain for as long as 28 days. On the other hand, the Philippines has at least 10 consecutive dry days, with western Luzon and northern Palawan having the longest with about 106 days.

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Sub-seasonal variations in rainfall during the *Habagat* and *Amihan* seasons are associated with tropical Intraseasonal Oscillations (ISO) (Bagtasa, 2021; Olaguera *et al.*, 2018a, 2022). Olaguera *et al.* (2022) found significant peaks at the 2- to 10-day (synoptic) and 30- to 60-day time scales, based on spectral analysis of rainfall during the *Habagat* season over Luzon and Mindanao Island stations. The 2- to 10-day mode of the ISO is the only significant mode over stations in the Visayas. They also found that extreme rainfall in this season is modulated by the northward propagating 30- to 60-day mode of the BSISO, with more extreme rainfall events occurring when the active (suppressed) convection associated with the BSISO is over the Philippines. Olaguera *et al.* (2021a) also found that the monsoon breaks in the early *Habagat* season in the Philippines usually occur during the suppressed phases (i.e., Phases 1–4) of the BSISO. Bagtasa (2021) examined the impact of the eastward propagating Madden–Julian Oscillation (MJO) during the *Habagat* and *Amihan* seasons. He found that TC activity is enhanced in Phases 5–7 of the MJO during the *Habagat* season. Rossby wave response due to TC heating enhances moisture transport, southwesterly winds, and rainfall on the west coast of the country during the *Habagat* season. During the *Amihan* season, a cyclonic anomaly is established over the Philippine Sea, which is induced by active convection over the Maritime Continent and MJO (i.e., in Phases 4–6). This anomalous cyclonic circulation enhances the northeasterlies and rainfall along the east coast of the country. It is known that the ISO can also modulate the diurnal cycle of rainfall. For example, Natoli and Maloney (2019) found that the diurnal cycle of rainfall is enhanced over the Philippine land mass at least a week prior to the arrival of the convective anomalies associated with the BSISO. Chudler *et al.* (2020) also found that offshore rainfall is enhanced during the active phases of the BSISO over Luzon.

3.4.4 ***Floods and Droughts***

Extreme rainfall has consequences for the occurrence of floods and droughts. As discussed previously, extreme rainfall and the lack thereof are measured in a variety of ways. In the case of floods and droughts, indices are used to measure how extremely wet or dry the conditions related to rainfall are.

On average, three to four significant floods occur every year in the Philippines (Abon *et al.*, 2016; Department of Public Works and Highways, 2004; Mercado *et al.*, 2018). From a January 2017 heavy rainfall and flood event, Olaguera *et al.* (2021b) analyzed the total rain, which was almost twice the climatological daily maximum rainfall for January in Cagayan de Oro City. In other parts of the Philippines, such as Davao Oriental, floods are considered a major natural disaster because of heavy rainfall and TCs (Cabrera & Lee, 2019, 2020). Among the high-risk areas in Davao Oriental, rainfall showed a greater contribution (~40%) to flooding compared to the slope of the region's topography (~24%).

While there are several definitions of drought, the particular type concerning rainfall is called a "meteorological" drought. There are several indices to categorize a specific event as a drought, aside from counting consecutive dry days. Salvacion (2021) used the Standard Precipitation Index (SPI) and the Standard Precipitation Evapotranspiration Index (SPEI) to determine how much rainfall and potential evapotranspiration deviate from normal. From 1958–2019, using TerraClimate, which is a mix of satellite and in situ data, 77–134 drought events were identified based on SPI, and 57–116 events based on SPEI. The magnitude of the drought ranged from 47–677 mm, with a duration of 2–11 months and an intensity of 60–800 mm/month.

Highly populated areas also experience urban drought (Porio *et al.*, 2019). In 1998, Metro Manila experienced drier conditions compared to Angat, but it was otherwise in 2016. Over Metro Iloilo, above-normal rainfall was experienced in January 2016 and started to decline in the following months, but the dry condition persisted from January to May 1998. Meanwhile, Metro Cebu experienced a decrease in rainfall of around 48% relative to normal from January to May 1998. While it was emphasized that El Niño caused the drought impacts in the metropolitan areas, the drought events were also influenced by several other factors, such as urbanization or land use change, which led to UHI effects.

Shearlines, which are formed by the convergence of cold northerly winds associated with eastward propagating cold fronts in the mid-latitude region and warm tropical easterlies, have also been examined in recent studies (e.g., Olaguera & Matsumoto, 2020; Olaguera *et al.*, 2021b,c). This synoptic system is one of the causes of heavy rainfall and flooding events, especially in the southern Philippines during the *Amihan* season. So far, only specific cases as well as their climatological characteristics have been examined in previous studies. Long-term trends and variability of heavy rainfall events related to the shearline warrant further investigation. Recent studies have also examined the decadal to interdecadal variability of rainfall, the onset of *Habagat*, and TCs in the country (e.g., Basconcillo & Moon, 2021; Kubota *et al.*, 2017; Olaguera *et al.*, 2018a;b), although the availability of longer and more homogenous datasets for the whole country remains an issue.

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3.5 Tropical Cyclone

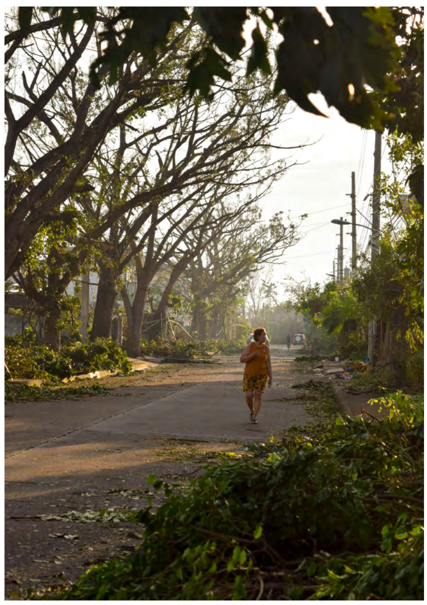
Situated in the Western North Pacific (WNP), the Philippines is among the most exposed and at-risk countries to TCs in the world (Asian Disaster Risk Reduction Center, 2020). Specifically, about 60% of total TCs that form in the WNP each year pass through the PAR (Lu *et al.*, 2021). The PAR is the Philippine forecast region designated by the World Meteorological Organization. While this section limits its review of TC-related studies in the PAR, regional studies in the WNP were included to provide a larger perspective on regional (e.g., WNP subtropical high) to planetary scales (e.g., ENSO).

There is no single definition of a TC season in the PAR, but there is general agreement that the more active season (MAS) typically begins in June and ends in December (Corporal-Lodangco & Leslie, 2017). The TC frequency during the MAS accounts for nearly 80% of the total annual TC frequency in the PAR, but TCs can still develop during the less active season (LAS). More notably, TC occurrences during the LAS in the Philippines and in Mindanao have increased by about 210% and 490%, respectively, since 2012 (Basconcillo & Moon, 2021).

Efforts to understand TCs in the PAR and their sources of variability and predictability have considerably increased in the last several decades. The majority of these recent reports put an emphasis on the observational analysis of the variability and periodicity of TCs and TC-associated hazards in the Philippines (e.g., Bagtasa, 2019; Corporal-Lodangco & Leslie, 2017; Desquitado *et al.*, 2020; Kubota *et al.*, 2017; Lu *et al.*, 2021). For example, it is reported that the Philippine TC activity peaks every 2–7 years, which implies that Philippine TC activity is driven by ENSO phases and occurrences (Corporal-Lodangco & Leslie, 2017). Likewise, the number of numerical TC studies that improve our understanding of TC dynamics and thermodynamics has also increased (Cruz & Narisma, 2016; Delfino *et al.*, 2022; Racoma *et al.*, 2016; Villafuerte II *et al.*, 2021). For instance, the underestimation of TC intensity and tracks in some of the parameterization schemes in the Regional Climate Model can be attributed to the dry mid-tropospheric environment and the lack of positive low-level vorticity in the Pacific Ocean in the simulations (Villafuerte II *et al.*, 2021).

DOST-PAGASA modified its TC classification system to provide a more accurate TC warning system to account for ground-based TC-associated damages caused by intense TCs and to maintain consistency with the global TC community (PAGASA, 2022). PAGASA maintained the five-tiered TC classification system based on maximum sustained wind speed but lowered the threshold values for the typhoon category (from 32.7 to 61.1 ms^{-1} to 32.7 to 51.1 ms^{-1}) and super typhoons (from >61.1 ms^{-1} to >51.4 ms^{-1}).

PhilCCA 2016 discussed the long-term trends and changes in observed TC frequency and intensity, as well as the large-scale systems that influence TC variability. However, due to the rapid growth of research, particularly in the last five years, these observations have been updated. The following subsections discuss these updates on the observed TC trends.



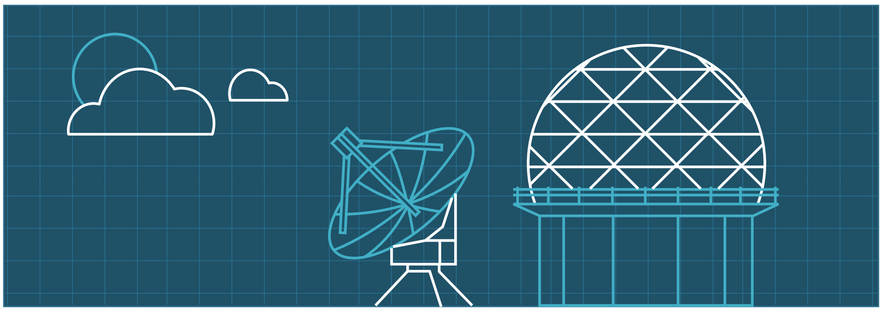
3.5.1 *Data Reliability and Homogeneity*

Most studies on TCs utilize different data sources depending on their intended application and objectives (Kang & Elsner, 2012; Knapp & Kruk, 2010; Lee *et al.*, 2020; Song *et al.*, 2010). Such differences introduce compound issues with TC data reliability and homogeneity, more particularly when conducting temporal and longitudinal analysis of various TC metrics (i.e., frequency, duration, and intensity). Of all TC metrics, TC intensity is arguably the most sensitive to unreliable and inhomogeneous TC data (Kim & Moon, 2021). For example, the Joint Typhoon Warning Center (JTWC) calculates the TC intensity based on the 1-minute averaged maximum sustained wind (JTWC, 2022), while the Regional Specialized Meteorological Center (RSMC) and DOST-PAGASA use 10-minute averages of maximum sustained wind (DOST-PAGASA, 2019; RMSC-Tokyo, 2022). This can be challenging for the analysis of TC intensity and its classification because those of the JTWC are reported to be 12% more intense than RSMC data (Atkinson, 1974).

Since 2017, DOST-PAGASA has issued the "Annual Report on Philippine Tropical Cyclones" (DOST-PAGASA, 2017), which contains post-analysis and detailed reports on each TC while inside PAR. In addition, DOST-PAGASA uses its Tropical Cyclone Guidance System, which is a collection of post-analyzed TC data (i.e., track and classification), mainly developed for statistical and graphical analysis of historical TC data in the PAR (DOST-PAGASA, 2005). However, because there is no study to date on the reliability of historical TC data in the Philippines, existing TC studies in the Philippines (and in the WNP) rely on best track data from either JTWC or RSMC.

There are several attempts to homogenize historical TC data from various agencies (Knapp & Kruk, 2010; Song *et al.*, 2010) using a wide array of objective (e.g., Dvorak method, Dvorak, 1975) and subjective (e.g., vortex identification threshold and historical accounts) techniques (Kim & Moon, 2021). Both techniques, however, require primary sources of information for validation, such as satellite observations and flight reconnaissance, which only became widely available in the 1960s, more commonly known as the satellite period (Kang & Elsner, 2012). In the absence of satellite observations during the pre-satellite period (i.e., prior to the 1960s), the reliability of TC intensity is put into question. By extension, the TC classification based on TC intensity, especially between tropical depression and tropical storm, cannot be free from reliability issues as well (Basconcillo & Moon, 2022).

There is general consensus among TC studies to use the late 1970s to early 1980s as the beginning of the reliable period of TC observations because of increased satellite observations, flight reconnaissance, and surface observations. Based on the relationship between TC intensity and frequency in the WNP while comparing JTWC and RMSC, the year 1984 is proposed as the beginning of the reliable TC period in the WNP (Kang & Elsner, 2012). Alternatively, the year 1985 is suggested as the start of the reliable TC period in the WNP that amply captures reliable observations based on the relationship between TC frequency and climate indices such as the PDO and ENSO (Kim & Moon, 2021).



3.5.2 *Sources of Variability*

Several reports suggest that TCs are modulated by different sources of variability that have modes ranging from the intraseasonal, seasonal, and interannual to the interdecadal (e.g., Bagtasa, 2020; Olaguera *et al.*, 2022; Zhang *et al.*, 2009). For example, in the intraseasonal modes, during the Habagat season, the active phase of the MJO (Bagtasa, 2020) and the BSISO (Olaguera *et al.*, 2022) provide favorable conditions for TC formation, which, in turn, affects increased TC rainfall occurrences in the Philippines. An active MJO and BSISO near the Philippines translate to increased convective activities, which can be precursors to TC development. Moreover, such intraseasonal variability can also modulate the position of the WNPSH, which considerably influences TC formation in the WNP and TC passages in the Philippines (Zhang *et al.*, 2009).

On interannual to seasonal timescales, previous reports show that the ENSO affects TC track, duration, and intensity. During El Niño, the mean location of TC genesis in the WNP is displaced eastward as the Walker circulation also shifts eastward. Such shifts result in longer TC duration and recurving tracks, which ultimately lead to reduced TC frequency in the PAR (Corporal-Lodangco *et al.*, 2016). On the other hand, during La Niña, the mean location of TC genesis is closer to the Philippines, which prompts more straight-moving tracks and shorter TC durations. Thus, more TCs form inside the PAR. It is important to note that changes in

TC intensity, track, and duration depend on the ENSO phases and occurrences.

The other known sources of interannual to seasonal TC variability in the WNP include the Indian Ocean Basin Wide (IOBW) SST, the Pacific Meridional Mode (PMM), and the WNP summer monsoon index (WNPMI). To emphasize such influence, Basconcillo *et al.* (2021) demonstrated that the combined influence of the WNPMI, IOBW, ENSO, and PMM resulted in the highest TC frequency record in the WNP during the satellite period. A cooler IOBW, warm PMM, and warm ENSO amplify the WNPMI intensity, resulting in an extended monsoon trough that highly favors increased TC development, particularly in the eastern half of the WNP. Such connections were further confirmed in a report that shows 43% of the TCs that formed in the Philippines from 1973 to 2013 during MAS were influenced by either the monsoon shearline, monsoon confluence region, or monsoon gyre (Fudeyasu & Yoshida, 2018).

On interdecadal to multidecadal timescales, it is reported that the recent increase of the so-called Christmas typhoons can be attributed to the PDO shifting to its positive phase in the early 2010s (Basconcillo & Moon, 2021). A positive PDO phase is related to favorable conditions for TC genesis, such as warm SSTs, an increase in moisture fluxes, and low-level vorticity. Moreover, the changes in SST during the positive phase of PDO can strengthen and modulate the southward migration of the WNPSH, which can then lead to an increase in landfalling TCs in the country. Furthermore, a recent study found that the positive phase of the AMO can enhance the Pacific Walker circulation. Such an event relates to an increase in SST and mid-level moisture across the Western Pacific, which creates a favorable environment for TCs (Basconcillo *et al.*, 2023).

3.5.3 *Long-Term Trends and Associated Hazards*

Despite the number of TC researches in the WNP, it is notable that there are only a handful of studies on the observed long-term trends of TCs in the Philippines. According to existing reports, there is a slight decreasing trend in the annual TC frequency from 1980–2015 (DOST-PAGASA, 2018) and the annual lifetime maximum intensity (LMI) from 1980–2011 (Corporal-Lodangco & Leslie, 2017) in the Philippines. A similar trend was found for MAS during the same time period (Corporal-Lodangco & Leslie, 2017), in which the decreasing signal during boreal summer is attributed to the northward shift in TC genesis location, which ultimately leads to reduced TC passage in the Philippines (Lee *et al.*, 2019). On the other hand, an increase in TC activity in the Philippines and in Mindanao during LAS from 2012–2020 has also been reported. The observed trends in both TC seasons were robustly attributed to shifts in the interdecadal modes of variability (i.e., PDO), which further confirms that TC occurrences in the Philippines follow a 10- to 12-year cycle (Basconcillo & Moon, 2021; Desquitado *et al.*, 2020). Furthermore, a sudden increase in annual TC activity in the Philippines has been detected since 2003, which can be attributed to teleconnection patterns associated with the positive phase of the AMO (Basconcillo *et al.*, 2023).

The long-term trends in TC observations in the Philippines are generally consistent with those in the WNP, which is not surprising because more than half of the TCs in the WNP pass through the PAR. Basconcillo & Moon (2022) summarized several studies that were undertaken on the trends and findings in different TC metrics in WNP (***Table 3.2***). The majority of these studies conclude that there is a decreasing trend in the annual TC frequency in the WNP from the mid-1990s to the early 2010s as a result of unfavorable conditions in TC development, strengthening of the WNPSH, weakening of the Pacific Walker circulation, and regional SST changes in the WNP.

Similarly, significantly decreasing TC activity in Southeast Asia from 1981 to 2019 has been observed during the boreal autumn (i.e., September to October), due to a wider WNPSH that steers TC passages in East Asia while avoiding intrusion into Southeast Asia (Basconcillo & Moon, 2022). Meanwhile, a significantly increasing trend in TC intensity and TC activity was observed during the boreal spring (i.e., MAM) from 2000–2022 in the WNP, which was attributed to the increase in Central Pacific El Niño events in the same time period (Duran & Basconcillo, 2023).

TC intensity and translation speed affect TC-induced rainfall (e.g., Racoma *et al.*, 2021). This means that stronger and slower-moving TCs can cause heavy and prolonged rainfall along the TC track (Racoma *et al.*, 2016, 2021). From 1951–2014, TCs induced more than 40% of total rainfall over Luzon, with the greatest contribution along the northwest coast at 54.2% and an increase in TC rain contribution of 16.9%–19.3% per decade since 2000 (Bagtasa, 2017). Moreover, from 1958–2017, a significant increasing trend of 6.0% per decade in the mean annual number of HPE days per decade and 12.7% per decade in the annual total HPE precipitation were indicated for the upper 85th percentile daily rainfall (Bagtasa, 2019). This region's high percentage contribution of TC-induced rainfall is attributed to non-landfalling TCs northeast of the Philippines, which cause extreme precipitation events in the area (Bagtasa, 2017, 2019; Olaguera *et al.*, 2022; Racoma *et al.*, 2021). The TCs act as an extension of the monsoon trough, which enhances the monsoon flow in the process. The interaction of the moist southwest monsoon flow with the mountainous areas of Luzon results in heavy precipitation. Additionally, 36% of the total rainfall extremes over Luzon are associated with TCs that are enhanced by intraseasonal variability such as the BSISO (Olaguera *et al.*, 2022). These TC-induced rainfall events may lead to flash floods, flooding, sediment influx, and land mass movements, e.g., landslides (Yumul *et al.*, 2012). However, to our knowledge, there is no available literature that describes the impact of TCs on the said hazards.

Table 3.2

List of literature related to multi-year variability of tropical cyclones (TC) in the Western North Pacific (WNP).

YEARS	MONTHS	BASIN	TC METRICS	GENERAL REMARKS	REFERENCE
1960–2011	Annual	WNP	TC frequency	Abrupt decrease in annual TC number from 1998–2011 to strong vertical wind shear and strong WNP subtropical high (WNPSH)	Liu & Chan, 2013
1975–2016	Annual	WNP	TC frequency	Decreased TC frequency from 1998–2016 due to the reduction of TC genesis in the southwestern part of the WNP	Liu & Chan, 2019
1979–2016	Annual; Oct–Dec	WNP	TC frequency	Decreased TC frequency from 1998–2016 due to negative Pacific Decadal Oscillation (PDO) phase	Zhang & Wang, 2016
1979–2011	Annual	WNP	TC frequency	Decreased TC frequency from 1995–2011 due to changes in vertical wind shear	Choi *et al.*, 2015
1960–2012	Annual	WNP	TC frequency	Decreased TC frequency from 1998–2009 to increase in vertical wind shear in the central Pacific and increased landfall in Taiwan due to changes in steering flow	Hong *et al.*, 2016
1979–2011	Annual; Oct–Dec	WNP	TC frequency	Decreased TC frequency from 1998–2012 due to changes in low–level vorticity and vertical wind shear	Zhang & Wang, 2016
1979–2016	Jul–Oct	WNP	Power dissipation index (PDI)	Increased PDI from 1998–2016 due to increased TC intensity	Tu *et al.*, 2018
1979–2011	Oct–Dec	WNP	TC frequency	Decreased TC frequency from 1995–2011 due to negative relative vorticity	Hsu *et al.*, 2014
1980–2011	Oct–Dec	WNP	TC frequency	Decreased TC frequency from 1996–2011 due to the weakening of the East Asian Winter Monsoon	Choi *et al.*, 2017
1989–2012	Jul–Oct	WNP	Intense TC frequency	Increased intense TC frequency from 2006–2012 mainly from September due to increased relative vorticity and strengthening of the monsoon trough	He *et al.*, 2017
1951–2008	Annual	WNP	Rapid TC intensification	A negative PDO phase can weaken the warm pool of the equatorial Pacific	Wang & Liu, 2016
1970–2015	Jun–Oct	WNP	TC frequency	Negative Interdecadal Pacific Oscillation results to more TC landfall in East Asia (EA)	Wu *et al.*, 2020
1979–2016	Jun–Nov	WNP	TC frequency	TC frequency in EA is correlated with WNPSH, more particularly in June to August	Camp *et al.*, 2018

SOURCE: ADAPTED FROM BASCONCILLO & MOON (2022)

From 1958–2017, a total of 28 storm surge events in the Philippines were described in the available literature based on storm surge and tidal observations and historical accounts (Needham *et al.*, 2015). However, this number is *likely* underestimated given that approximately four to six storm surge events are usually observed in a year (Arafiles *et al.*, 1984). Storm surge events are often underestimated and/or unrecorded because of poor observations and a lack of reliable TC data. Typhoon Haiyan in 2013 registered the highest storm surge level in recent history of up to 8 m (Mas *et al.*, 2015). In fact, 7 out of the 10 highest storm surge levels from 1880–2013 in the WNP are recorded to have happened in the Philippines (see Table 3 in

Needham *et al.*, 2015). Among these events, the top four storm surge events, which happened in the Philippines, registered storm surge levels of more than 7 m. The coastal geometry (e.g., shape, orientation, and geography) of the Philippines and its location with prominent TC passages strongly influence the magnitude of storm surge impacts along its coastlines (Arafiles & Alcanjes, 1978). Such impacts translate to an annual average cost of damages amounting to almost US$1 million (Henderson, 1988). Typhoon Haiyan reportedly caused US$13 billion in damages to properties, along with thousands of casualties (Needham *et al.*, 2015). To date, there remains a wide gap in the understanding of storm surge occurrences and their dynamics in the country.

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While the poleward migration of the location of TC LMI is adequately reported in the WNP, to date, such a trend has not yet been described or reported in the Philippines. In the WNP, it is reported that weak TCs have poleward-shifted to about 1° N since 1980 (Zhan & Wang, 2017), where the higher-latitude TCs during the MAS contribute more to the poleward migration compared with the LAS (Feng *et al.*, 2021).

Similarly, there is also no report on the trend of TC translation speeds in the Philippines. It is reported that there has been a global slowdown in TC translation speed since 1950, and such a trend is also found in the WNP (Kossin, 2018). However, a recent report shows that there is no significant trend in TC translation speed in the WNP after 1981 (Zhang *et al.*, 2020), which non-trend may arise from TC data uncertainties in the pre-satellite period (Moon *et al.*, 2019).

3.5.4 *Tropical Cyclone-Associated Damages*

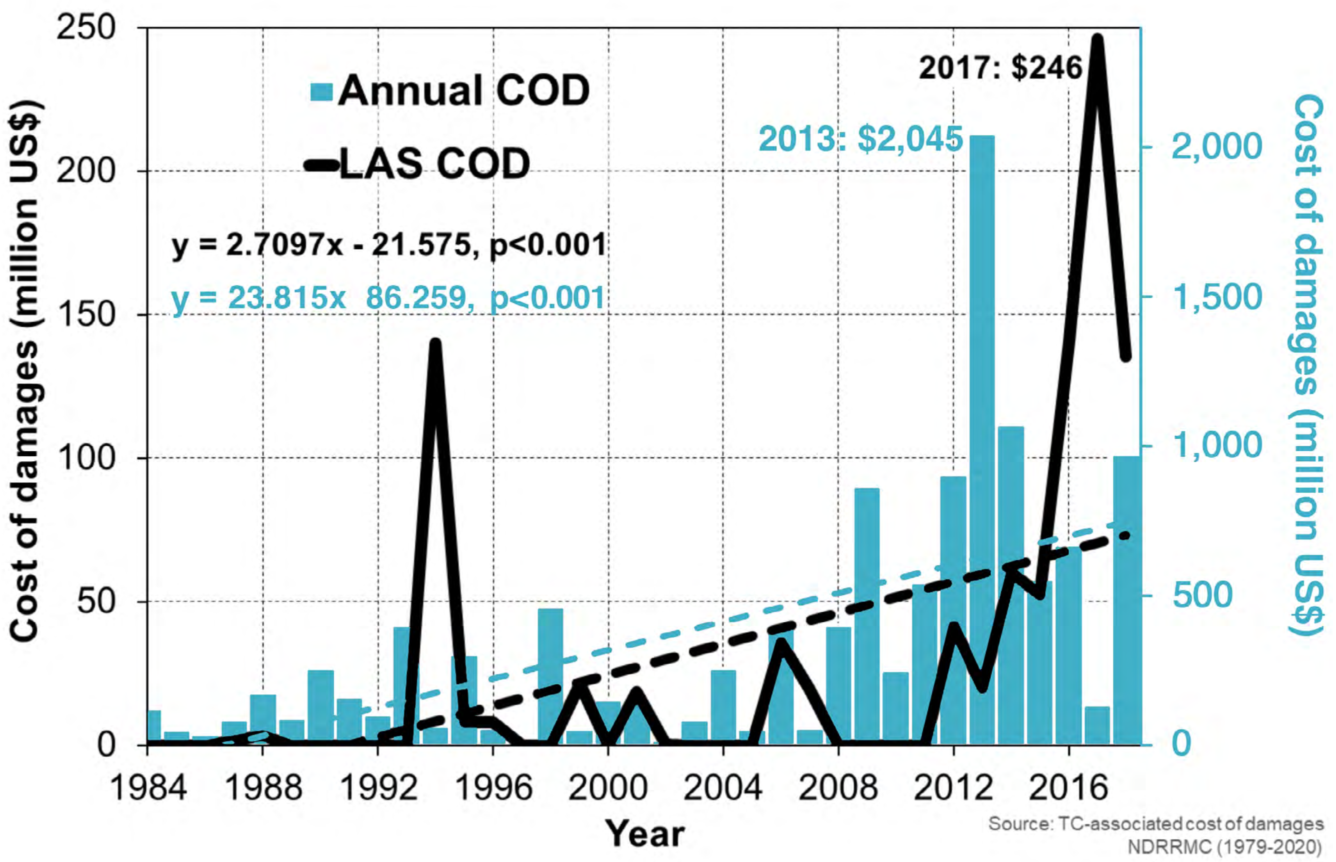
There is a significantly increasing trend in the annual cost of damages associated with TCs in the Philippines (Basconcillo & Moon, 2021) from 1984–2018 (***Figure 3.2***). The highest cost of damages was recorded in 2013, *likely* due to Typhoon Haiyan that year. An abrupt decrease in the annual cost of damages has been observed since 2013, but the same cannot be said for the LAS, where an increasing cost of damages has been noted since 2012.

More particularly, the last five years (2017–2021) saw the highest total damages (Guha-Sapir *et al.*, 2009) associated with TCs in the Philippines, which are due to four strong TCs: Typhoon Rai (Odette), Typhoon Mangkhut (Ompong), Super Typhoon Goni (Rolly), and Typhoon Vamco (Ulysses). Moreover, from 2014–2017, 39.2% of the natural disasters monitored by the Philippine National Disaster Risk Reduction and Management Council were caused by flash floods (Padagdag, 2018), which, in turn, were caused by extreme precipitation events associated with TCs.

In terms of economic activity, it is reported that the areas with a 5-year return period of TC frequency can lead to about 1% of losses to national economic activity, while those rare storms (i.e., TCs with a return period of 20–50 years) can cause at least 2% of a reduction in the national economy (Strobl, 2019). Areas in Region VIII (i.e., Eastern Visayas) and Region II (e.g., Cagayan Valley) are expected to have the highest economic activity loss of 7.58% and 1.60%, respectively, due to frequent storms, and up to 20% on rare storms (see Table 2 in Strobl, 2019) because these areas typically experience the highest TC passage frequency relative to the rest of the Philippines.

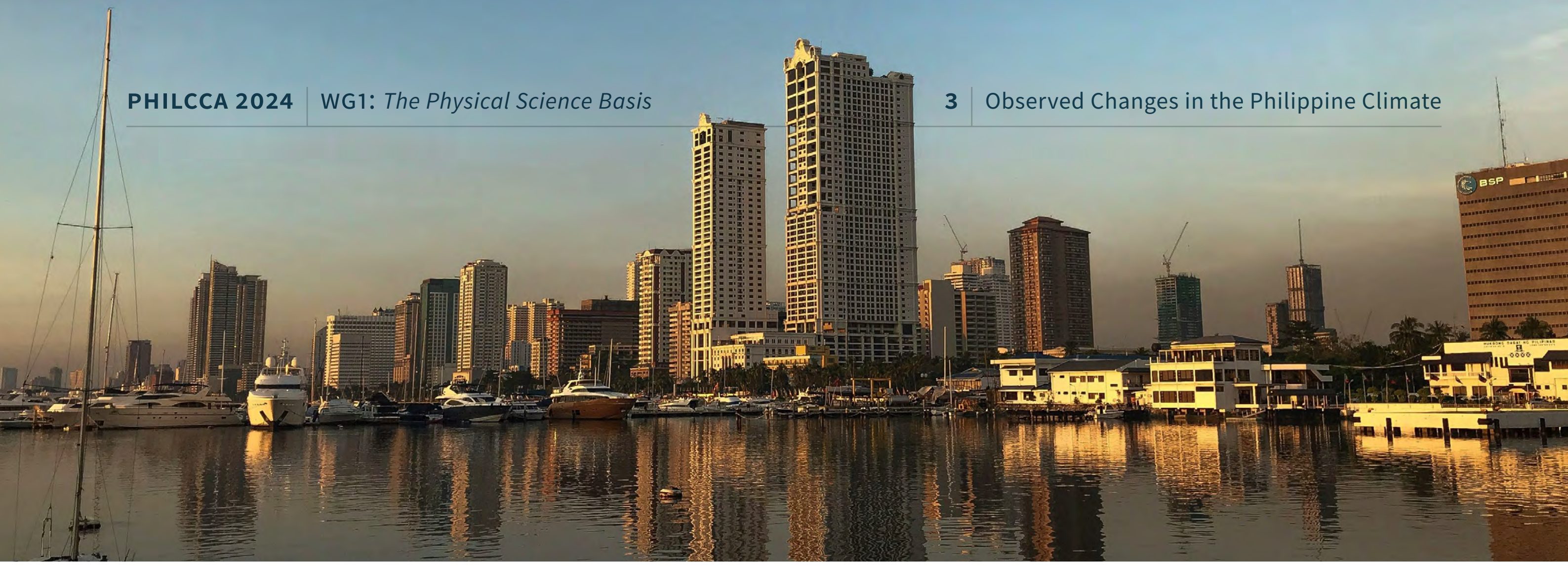
Figure 3.2

Cost of damages associated with tropical cyclones in the Philippines.



The red (black) bar (line) indicates the annual (less active season, LAS) cost of damages from 1984–2018. The significant trend of the cost of damages during LAS (black) and in annual terms (red) increased (decreased) in 2012

SOURCE: ADAPTED FROM BASCONCILLO & MOON (2021)



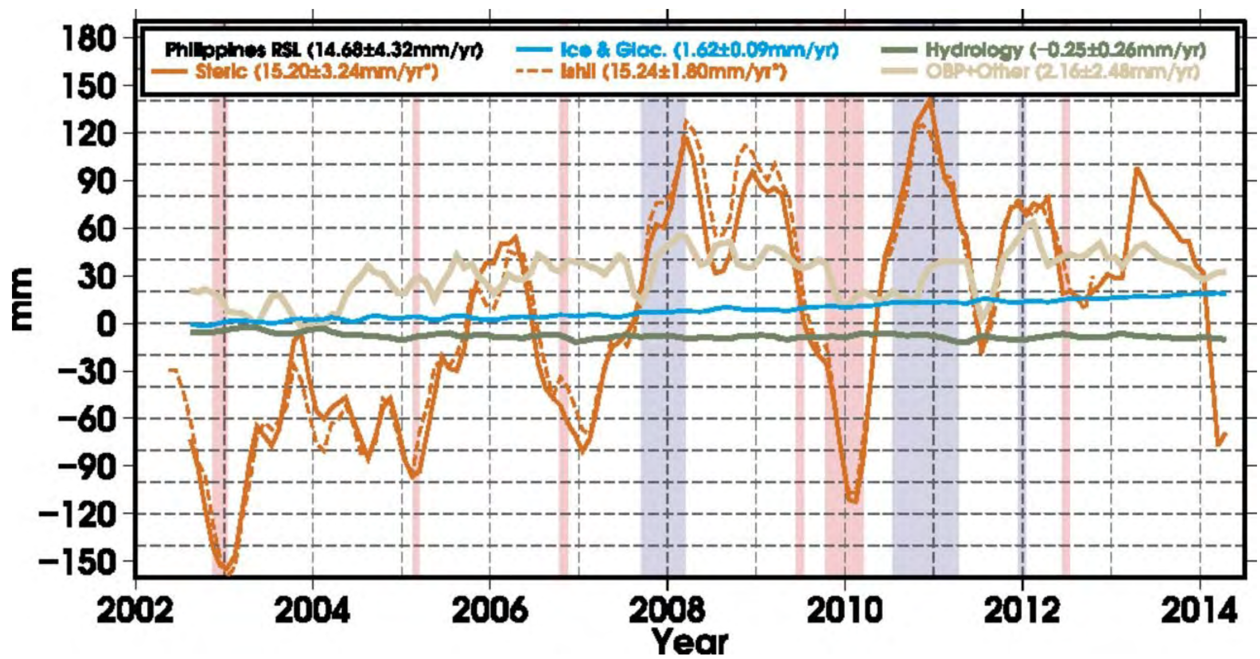
3.6 Sea Level Rise

Global sea level change is one of the major threats associated with climate change. Numerous assessments have confirmed that the melting of ice sheets and glaciers and the expansion of warm sea waters are the primary causes of this change (Fox-Kemper *et al.*, 2021). Moreover, the rate of sea level change may vary from one region to another, as it is also driven by ocean currents, atmospheric circulation patterns, and other modes of climate variability such as the ENSO, the PDO, and the North Atlantic Oscillation. Land water storage (i.e., dams and reservoirs), crustal movement induced by glacial isostatic adjustment (GIA), and land subsidence are the other factors that may contribute to regional differences in sea level change. Since there are significant multidecadal variations in regional sea level, local rates of sea level rise can be higher or lower than the global mean.

Previous studies such as Rietbroek *et al.* (2016) and Kahana *et al.* (2016) used satellite datasets, and both showed that the highest sea level change can be found over the east Philippine Sea. Rietbroek *et al.* (2016), using Gravity Recovery and Climate Experiment gravity observations and sea level anomalies from altimetry, found a well-above average annual sea level rise of 14.7 ± 4.39 mm/year in the vicinity of the Philippines (see ***Figure 3.3***).

Figure 3.3

Time-variable sea level contributions to the east of the Philippines.



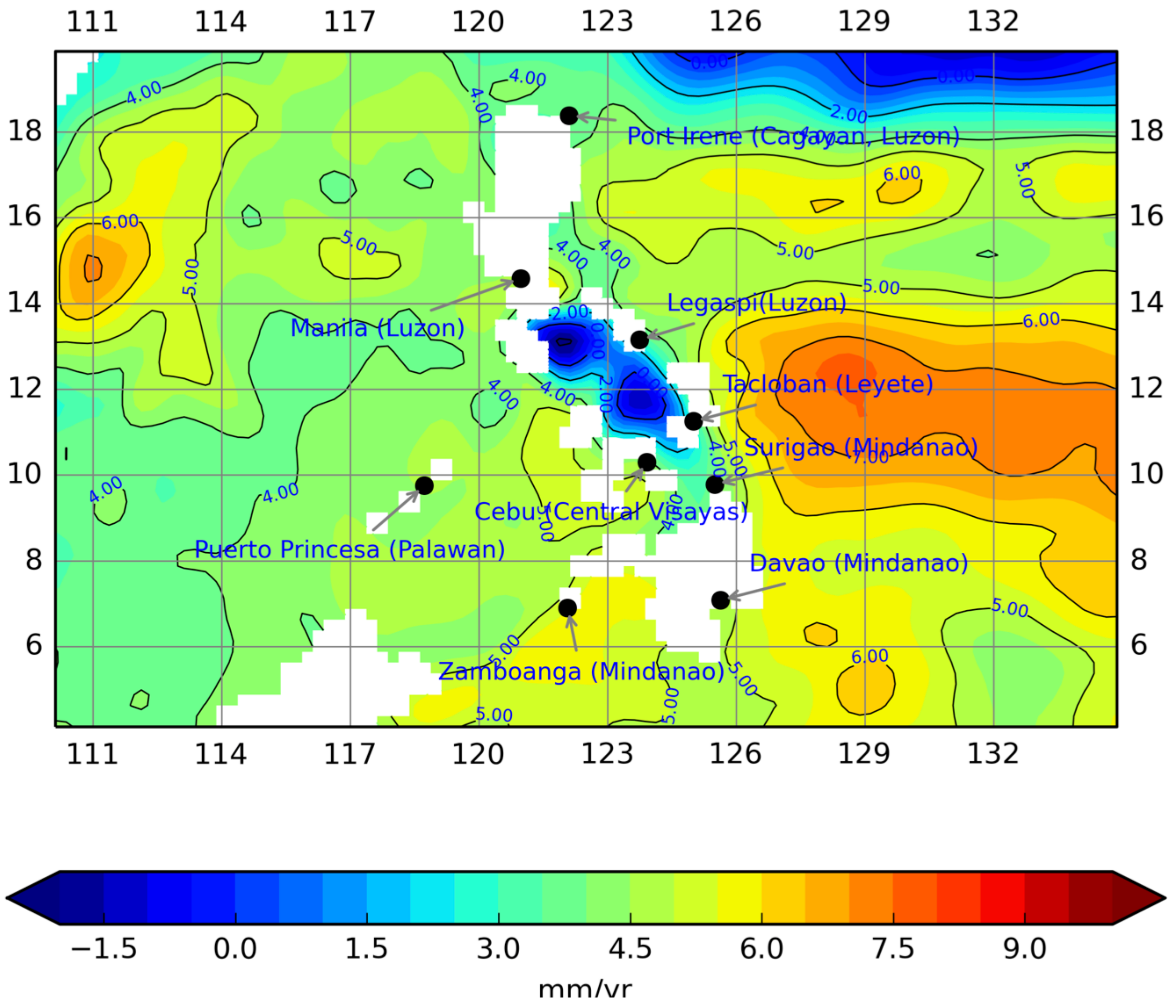
Warm (El Niño, red) and cold (La Niña, blue) phases are highlighted whenever the multivariate ENSO index gets larger than 1 or smaller than −1, respectively

SOURCE: ADAPTED FROM RIETBROEK *et al.* (2016)

Kahana *et al.* (2016) examined the satellite altimetry observations from the Archiving, Validation, and Interpretation of Satellite Oceanographic (AVISO) data from 1993–2015 and found that sea level has risen by about 5–7 mm/yr over the Philippine Sea, which is about twice the global average of 2.8–3.6 mm/yr taken from 1993–2010. Sea level rise by as much as 4.5–5 mm/yr was also observed to the east of Samar and Leyte and regions along the southwestern coasts of the Central and Western Visayas, and east of Mindanao and south Zamboanga (see ***Figure 3.4***). The study indicated that the large increase is partly due to natural modes of ocean variability, such as ENSO and PDO, and partly due to an anthropogenic signal, which will continue regardless of the natural oscillations, in agreement with regional sea level studies (Hamlington *et al.*, 2014).

Figure 3.4

Sea level changes in the Philippine region from 1993–2015 produced from the Archiving, Validation, and Interpretation of Satellite Oceanographic satellite observations.



Largest rates of 4.5–5 mm per year are observed east of the islands of Leyte and Samar, and Mindanao, south of Zamboanga, and along the south-western coasts of Central and Western Visayas

SOURCE: ADAPTED FROM KAHANA *et al.* (2016)

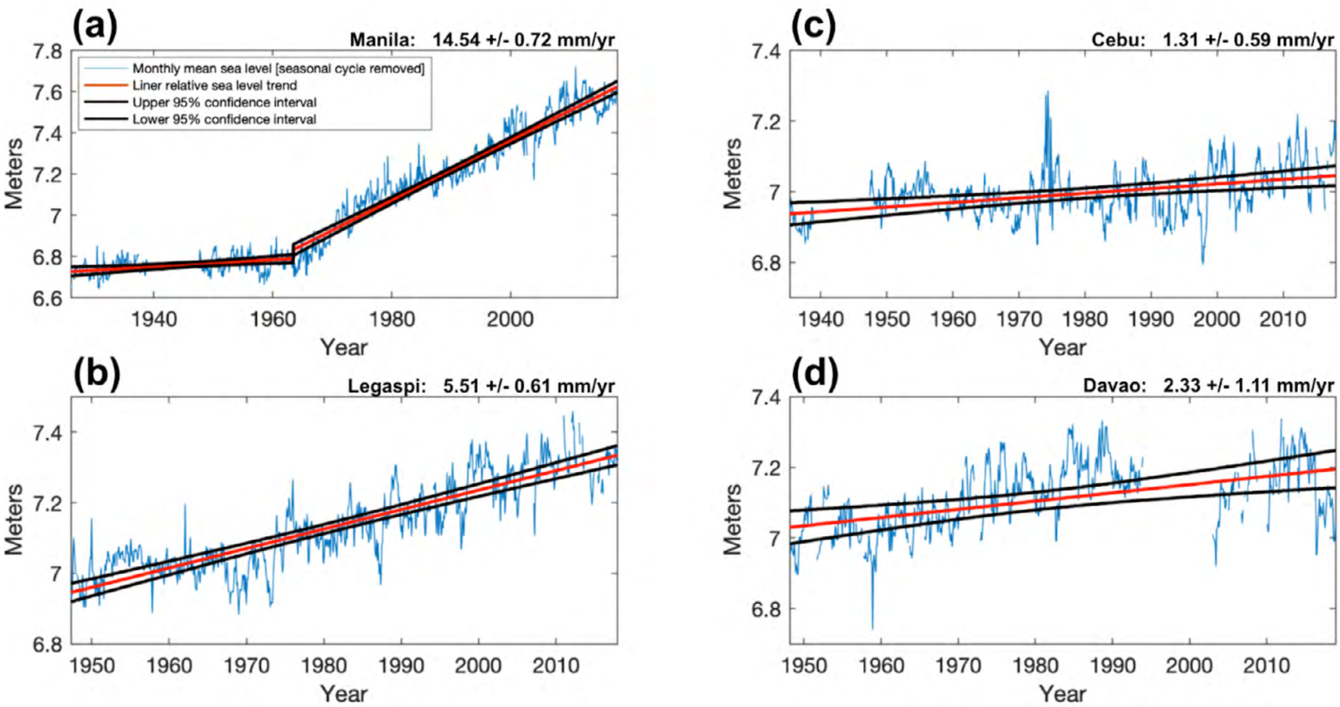
Kahana *et al.* (2016) also examined the tide gauge measurements of sea level that are distributed across the country and found a rapid increase in the sea level over Metro Manila. However, it was noted that these measured levels may have been influenced by long-term subsidence from excessive groundwater extraction in the metropolis. Moreover, coastal tide gauge records around the Philippines indicate a general pattern toward increased sea levels over the past 50 years. These tide gauges measure the sea surface height relative to the land, which might be moving vertically at comparable rates. They also include changes resulting from the vertical motion of the land and show different sea level trends for different locations around the Philippines. Presented in ***Figure 3.5*** are relative sea level trends in selected stations in the country that are sourced from the National Oceanic and Atmospheric Administration (NOAA, n.d.). Each plot shows the monthly mean sea level without the regular seasonal fluctuations due to coastal ocean temperatures, salinities, winds, atmospheric pressures, and ocean currents. The long-term linear trend is also shown, including its 95% confidence interval. The plotted values are relative to the revised local reference datum as established by the Permanent Service for Mean Sea Level.

Digital elevation models (DEMs) are widely used to assess changes in sea level. Santillan and Makinano-Santillan (2016) assessed the vertical accuracy and uncertainty of three global DEMs (e.g., Advanced Land Observing Satellite (ALOS) World 3D-30m (AW3D30), ASTER Global DEM Version 2 (GDEM2), and SRTM-30m) as inputs to elevation-based sea level rise vulnerability assessment over Mindanao. They found that all three DEMs tend to overestimate elevation and have high uncertainties. They therefore suggested that the accuracy and uncertainties of these DEMs should be considered when mapping inundations due to sea level rise over Mindanao.

Overall, findings indicate that local sea level rise is higher in the Philippine seas.

Figure 3.5

The relative sea level trend in Manila, Legazpi, Cebu, and Davao.



(a) Manila, where the trend is 14.54 mm/year with a 95% confidence interval of +/– 0.72 mm/yr based on monthly mean sea level data from 1963 to 2017, which is equivalent to a change of 4.77 feet in 100 years. The 1901–1969 trend is 1.82 +/– 0.41 mm/yr.

(b) Legazpi, where the trend is 5.51 mm/year with a 95% confidence interval of +/– 0.61 mm/yr based on monthly mean sea level data from 1947 to 2017, which is equivalent to a change of 1.81 feet in 100 years.

(c) Cebu, where the trend is 1.31 mm/year with a 95% confidence interval of +/– 0.59 mm/yr based on monthly mean sea level data from 1935 to 2017, which is equivalent to a change of 0.43 feet in 100 years.

(d) Davao, where the trend is 2.33 mm/year with a 95% confidence interval of +/– 1.11 mm/yr based on monthly mean sea level data from 1948 to 2018, which is equivalent to a change of 0.76 feet in 100 years.

SOURCE: SEA LEVEL TRENDS IN NOAA (NOAA, N.D.)

However, Strassburg *et al.* (2015) found that the regional sea level trends in Southeast Asia are some of the highest observed in the modern altimeter record that now spans two decades. Initial comparison of global sea level reconstructions indicates that 17-year sea level trends over the past 60 years exhibit good agreement with decadal variability associated with the PDO and related fluctuations of trade winds that vary dramatically over the studied period. This historical variation suggests that the strong regional sea level trends observed during the modern satellite altimeter record will *likely* abate as trade winds fluctuate on decadal and longer timescales. Furthermore, by removing the contribution of the PDO to sea level trends in the past 20 years, the rate of sea level rise is greatly reduced in the Southeast Asia region.

3.7 Directions for Future Studies

This chapter briefly summarizes the recent literature on local drivers and changes in the Philippine climate. Some key issues that have yet to be addressed are the following:

1. The classification of stations for estimating the urbanization effect remains a challenge in urban climate studies. Manalo *et al.* (2021) showed the clear urbanization effect using satellite night lights; however, several factors, such as the local climate zone, must also be considered to fully illustrate the differences in urban stations. This suggests further exploration of other methods using integrated procedures, machine learning, remotely sensed land use data, and other local factors affecting temperature measurements in the study area. The role of aerosols, which can enhance atmospheric instability, green infrastructure, and various methods of measuring temperature on different surfaces need to be further explored.

2. While long-term trends and extremes in temperature have been assessed in previous studies, the different drivers of temperature variability in the country have yet to be clarified. The MJO has been shown to enhance cold surges during the Amihan season over tropical southeast Asia (Bagtasa, 2021; Pang *et al.*, 2018), which bring cold temperatures over the Philippines. The southward expansion of the Siberian-Mongolian High may also affect the cold northeasterlies reaching the Philippines during the *Amihan* season. The role of these two large-scale systems on surface temperature variability in the country warrants further investigation in future studies.

3. The climatology, variability, and long-term trends of extreme winds are still a research gap. Extreme winds, especially those associated with TCs, often lead to catastrophic damage to infrastructure and the loss of human lives. This knowledge gap needs to be addressed in future research.

4. Estimation of local sea level rise in coastal communities has remained an enormous challenge, especially in planning and enhancing climate resilience and disaster risk reduction. Additionally, because the majority of rural communities living along the coasts rely heavily on the products and services provided by marine resources, studies on the impacts of ocean warming on the country, such as ocean acidification and deoxygenation, need to be undertaken.

5 The absence of reliable historical TC data is one of the most important challenges to TC research in the Philippines. To address such problems, a longitudinal analysis of existing TC data is suggested to improve the consistency and agreement in TC trend analysis. Moreover, the use of TC frequency and intensity alone as indicators of present TC trends may not be enough to represent the overall TC activity in the Philippines. The use of spatiotemporal indices (e.g., Accumulated Cyclone Energy, power dissipation index, Genesis Potential Index, and others) in the analysis is highly encouraged in the global TC research community, as their use integrates the frequency, intensity, and duration of TCs. The use of such TC metrics has been limited in the existing literature on the Philippines.

6 Several studies reported an increase in TC activity during the LAS (e.g., Basconcillo & Moon, 2021; Corporal-Lodanco & Leslie, 2016). However, the long-term variability and trends during the TC quiescent season (i.e., MAM), when the lowest TC activity is often observed, remain less understood. Olaguera *et al.* (2023b) also found that weaker TCs (i.e., non-TC vortices) contribute significantly to rainfall variability in the Philippines. They found that these vortices are more frequent during the DJF season and have the highest contribution to the mean daily rainfall in northeast Mindanao. The occurrence frequency of these non-TC vortices was also found to be modulated by the active phases of the BSISO and MJO, when both are transitioning from the Maritime Continent to the WNP. However, the trends in rainfall associated with these non-TC vortices were not examined in their study and require further investigation.

7 Moreover, several knowledge gaps in the areas of TC dynamics, variability, and associated hazards in the Philippines have already been identified. For example, it is interesting to note the lack of studies on the effects of surface and subsurface ocean properties in regional and marginal seas (e.g., West Philippine Sea, the Sulu Sea, and other inland seas) on TC dynamics and variability in the Philippines. Similarly, there is limited literature on the relationship between TC activity in the Philippines and the other modes of climate variability (e.g., PMM, Nino West, Warm Pool SST, and others) that are driven by changes in oceanic properties. Thus, there is a need to regularly revisit and update the long-term trends in TC variability and TC-associated hazards (i.e., storm surge, flooding, mass movement, and severe winds).

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Projected Future Changes in the Philippine Climate

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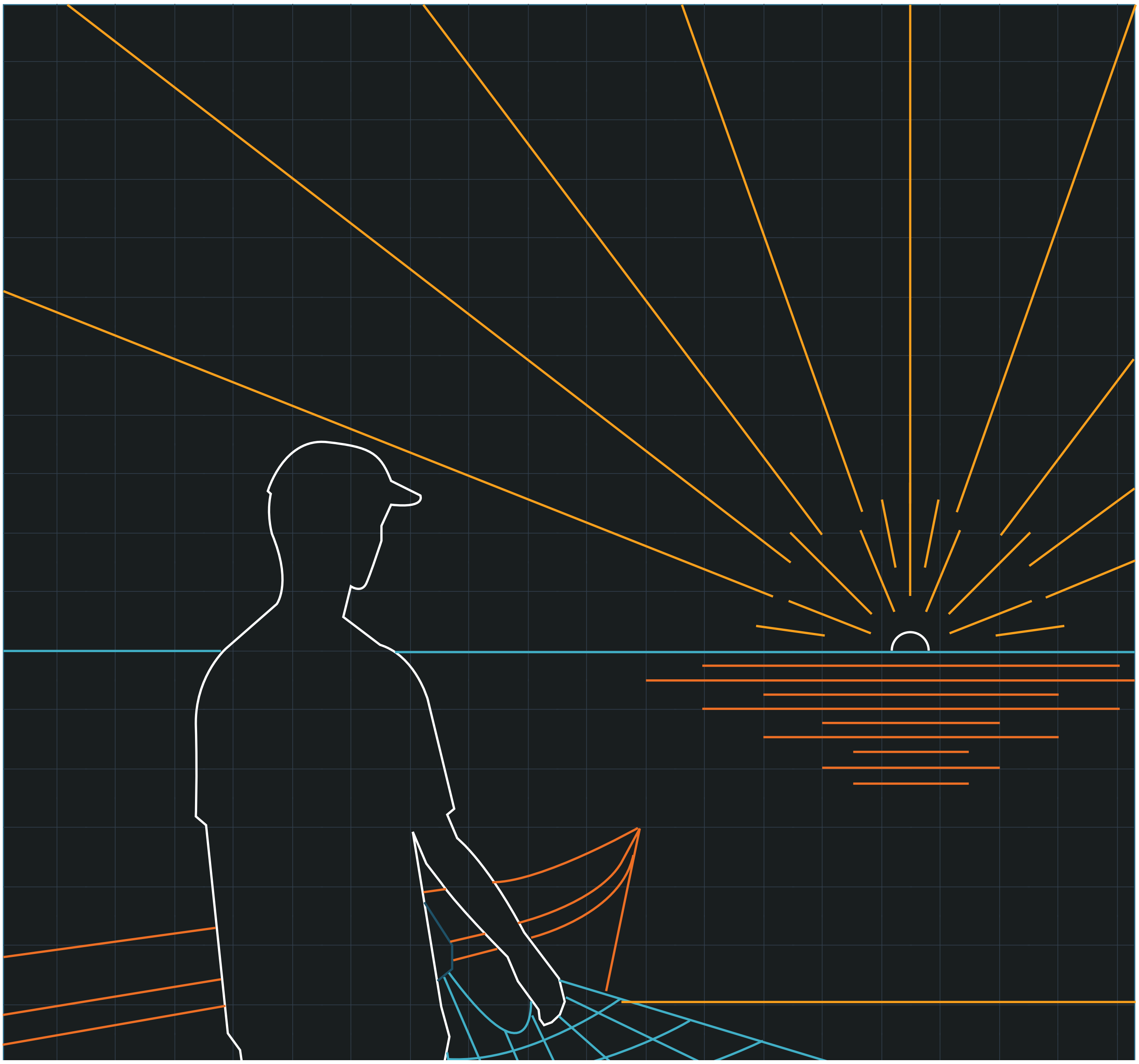
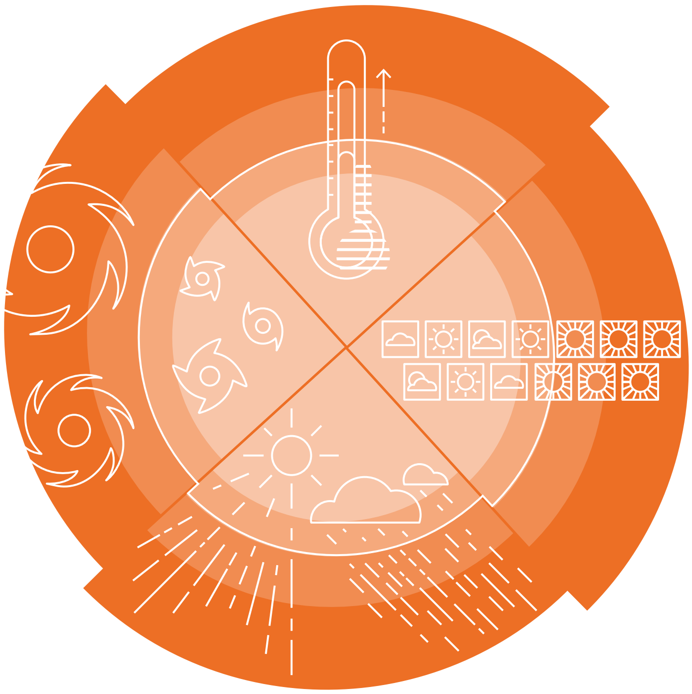


4.1 Chapter Summary

In the last five years since the first release of the Philippine Climate Change Assessment (PhilCCA) Report (Villarin *et al.*, 2016), much progress has been achieved in providing localized climate change projections in the country. Recent studies focused primarily on providing multi-model climate projections, given the known uncertainties in climate projections as recognized earlier. From the single model Special Report Emissions Scenarios (SRES), which became the basis of earlier projections in the Philippines (DOST-PAGASA, 2011), 12 dynamically downscaled climate projections assuming the RCP 4.5 and RCP 8.5 have been realized recently (DOST-PAGASA, MO, & ADMU 2021). Both dynamical and statistical downscaling approaches have also been conducted using the Representative Concentration Pathways (RCPs). The most recent shared socioeconomic pathway (SSP)-based projections have also been made available through an online platform known as the Climate Change Knowledge Portal (CCKP) of the World Bank Group, which allows users to visualize projections and download the raw data from the native global climate model (GCM) resolutions.

Figure 4.1

Projected changes in the Philippine climate



SOURCE: DOST-PAGASA (2018) AND DOST-PAGASA, MANILA OBSERVATORY, & ATENEO DE MANILA UNIVERSITY (2021)

Various studies have indicated projected changes in Philippine climate (***Figure 4.1***). Multi-model projections reveal a potential increase in the annual mean temperature of the Philippines that ranges from 2.5 °C (assuming the RCP 4.5) to as high as 4.1 °C with the RCP 8.5 by the end of the 21st century (DOST-PAGASA, 2018). Seasonal analyses have further shown that a slightly higher increase in mean temperature of about 1.3 °C–2.2 °C is projected during the hotter months of March to May (MAM) by the mid-21st century (Villafuerte *et al.*, 2020; World Bank Group, 2021). These projected changes in mean temperature are associated with increases in the intensity and duration of extreme temperature events, as represented by various extreme indices (DOST-PAGASA, MO, & ADMU, 2021).

Unlike temperature, there is large disagreement among the models when it comes to projected changes in rainfall. Some models indicate a wetter future, while others project drier conditions. Future changes in rainfall can go as high as 40% or even larger increases or decreases in many areas across the country by the mid-21st century (DOST-PAGASA, 2018; Villafuerte *et al.*, 2020). Projected changes in rainfall extremes described by various extreme indices representing intensity, frequency, and duration can be found in DOST-PAGASA, MO, & ADMU (2021). An intensity-based index represented by the maximum 1-day rainfall (Rx1day) indicates an increase of approximately 20%–25% over western and southern Luzon, southern Visayas, and western and southeastern sections of Mindanao by the late 21st century based on the multi-model median of projected changes.

For the first time, regionally downscaled climate simulations have been used to investigate tropical cyclones (TCs) affecting the country, which could partly be attributed to increased computing resources and greater collaboration among scientists here and abroad. Model evaluations reveal some limitations in capturing the climatological characteristics of TCs, including the difficulty of representing TC tracks and intensities (Gallo *et al.*, 2019; Tibay *et al.*, 2021; Villafuerte *et al.*, 2021). Multi-model projections and consensus suggest a slight decrease in TC occurrence over the Philippine Area of Responsibility (PAR) but more intense TCs in the future based on the RCP 8.5 scenario (Gallo *et al.*, 2019).

Despite recent developments in regional climate model (RCM) simulations, particularly in collaborative work among institutions in the Philippines, Southeast Asia, and the international modeling community, challenges in model biases and uncertainty remain and need to be resolved. Gaps in observational data likewise need particular attention. Most importantly, direct involvement and strong collaboration with the users of climate information are needed to allow for the co-creation of relevant climate information that can inform climate adaptation and mitigation policies.

4.2 Introduction

The Philippines, being an archipelagic country characterized by complex topography, is among the most vulnerable countries in the world to climatic hazards. Localized climate projections are therefore important for the country to manage climate change risks (Daron *et al.*, 2018). Hence, a number of studies have been carried out recently to provide high-resolution climate change projections. Providing this kind of information was achieved using either dynamical (i.e., RCMs that downscale GCMs) or statistical downscaling methods. A brief description of these two methods is provided in Villafuerte *et al.* (2020), and a comprehensive historical account of how they were achieved in the country has been discussed by Daron *et al.* (2018).

This chapter provides a brief background on the methods used in deriving the climate change projections for the Philippines (Section 4.3), which is the basis for the projected future changes in temperature (Section 4.4), rainfall (Section 4.5), and TCs (Section 4.6). The challenges and future direction are then presented in Section 4.7.

4.3 Development of Climate Change Projections

The projected changes in climate of the country are obtained through any of the following methods:

1. an RCM is used to dynamically downscale an SRES-based scenario from two GCMs (DOST-PAGASA, 2011);
2. statistically downscaled SRES-based multi-GCMs (Basconcillo *et al.*, 2016);
3. ensemble mean of RCP-based multi-GCM interpolated to high-resolution grids (Salvacion, 2017);
4. RCP-based multi-GCMs that are dynamically downscaled at high-resolution using multi-RCM simulations (e.g., DOST-PAGASA, 2018; DOST-PAGASA, MO & ADMU, 2021; Gallo *et al.*, 2019; Villafuerte *et al.*, 2020); and
5. SSP-based country-masked values taken from multiple Coupled Model Intercomparison Project Phase 6 (CMIP6) participating GCMs.

Table 4.1 summarizes the different approaches to providing these projections, which were assessed in this report.

Table 4.1

Summary of the different methods used in deriving climate change projections for the Philippines

METHOD USED	SCENARIO	GLOBAL CLIMATE MODELS (GCMS) INCLUDED	FUTURE TIME PERIODS AND DOMAIN COVERED	REFERENCES
Dynamical downscaling with the use of PRECIS	Special Emissions Report Scenario (SRES) B2, A1B, and A2	ECHAM4 and HadCM3Q0	2031– 2060, 2071–2100 (Philippines)	DOST-PAGASA, 2011
Statistical downscaling using the MOSSAIC model developed by Food and Agriculture Organization and then spatially interpolated using the Analyse Utilisant le RELief pour l'HYdrométéorologie (AURELHY) technique	SRES A1B and A2	BCM2, CNCM3, and MPEH5	2011–2040 (Philippines; Analyses for Cagayan Valley only); 2010–2050 (entire Philippines with focus on 24 river basins)	Basconcillo *et al.*, 2016; Tolentino *et al.*, 2016
Spatial interpolation to derive 5km grid spacing; the WorldClim dataset	RCP 8.5	Average values of 18 GCMs	2041–2060 (World; analyses for Philippines only)	Salvacion, 2017
Dynamical downscaling of GCMs with the use of multiple RCM simulations	RCP 4.5, RCP 8.5	Combination of at most 8 unique GCMs downscaled by 3 different Regional Climate Models	Varies from a complete set of model simulations covering the entire period of 2005–2099 and select time periods of 2035–2065 only. The domain varies from the entire Southeast Asia (in the case of Coordinated Regional Climate Downscaling Experiment Southeast Asia (CORDEX SEA) simulations) to the Philippines extending to western Pacific	DOST-PAGASA, 2018; Gallo *et al.*, 2019; Villafuerte *et al.*, 2020; DOST-PAGASA, MO, and AdMU, 2021
CMIP6-derived projections provided at a uniform 1 degree by 1 degree resolution on an online platform called the CCKP	SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5	Eleven CMIP6 Coupled Model Intercomparison Project Phase 6 GCMs and their ensemble mean	Various time slices: 2020–2039, 2040–2059, 2060–2079, and 2080–2099	World Bank Group (2021)

4.4 Projected Changes in Temperature

Temperature projections for the Philippines downscaled from earlier CMIP outputs show notable increasing trends throughout the 21st century relative to the 1971–2000 baseline (***Figure 4.2a***). The downscaled projections from SRES A1B (DOST-PAGASA, 2011; Rahmat *et al.*, 2014) and RCP 8.5 (DOST-PAGASA, 2018; Villafuerte *et al.*, 2020) are comparable in both the mid-21st century and late-21st century (with slight variations in the time period between datasets; see ***Table 4.1*** in Section 4.3). The temperature anomalies from the SRES A1B experiments range from +1.8 °C to +2.2 °C for the mid-21st century and +2.7 °C to +3.8 °C for the late-21st century (DOST-PAGASA, 2011), while values from the RCP 8.5 experiments range from +1.2 to +2.3 and +2.5 to +4.1 for the same time periods. Approximate values were obtained for northern portions of Luzon in the statistical downscaling experiments of Basconcillo *et al.* (2016) on three global model outputs driven by A1B and A2 scenarios, but these were for an earlier future time slice (2011–2040).

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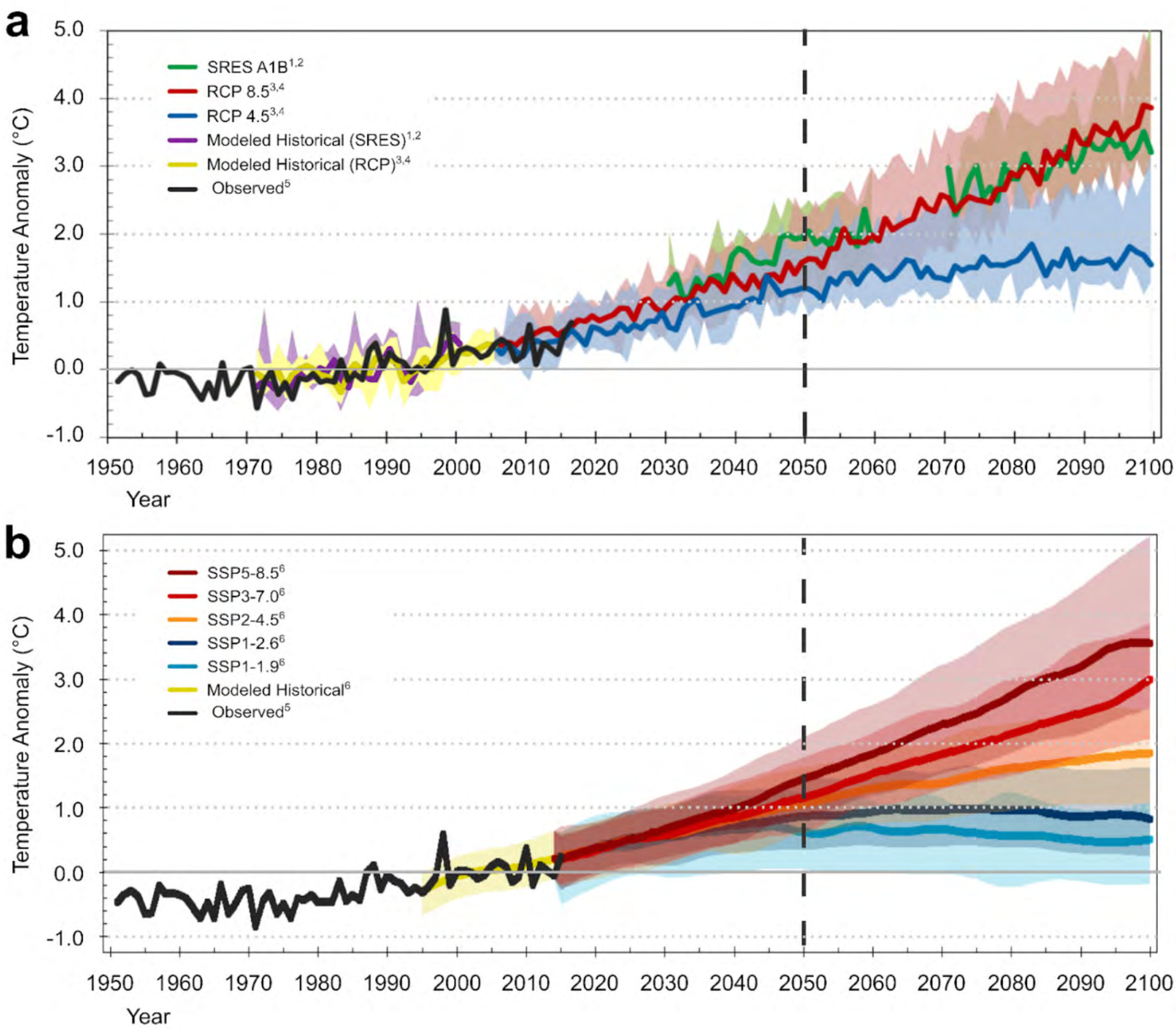
A less warmer future due to a slightly lower change in the country-averaged mean temperature (+0.9 °C to +1.9 °C) is suggested for the mid-21st century under the RCP 4.5 (DOST-PAGASA, 2018). This warming subsequently plateaus toward the end of the century, with mean temperature changes of only +1.3 to +2.5 by the late 21st century—the lowest among the three downscaling scenarios.

The aforementioned studies unanimously suggest that the projected increase in temperature will be relatively uniform throughout the country, with the possibility of slight variations on monthly and seasonal scales. Villafuerte *et al.* (2020) pointed out that the highest temperature increase is projected for the MAM season in most parts of the Philippines. However, Salvacion (2017) showed that the highest temperature increase in the eastern and western parts of the country will be from October to February and from June to September, respectively. This inconsistency could be attributed to the difference in the methods used in downscaling global projections to generate localized or national-scale values. Specifically, the ~5-km projection WorldClim dataset (Hijmans *et al.*, 2005) used in Salvacion (2017) was produced using an interpolation technique that does not consider local atmospheric processes (Daron *et al.*, 2018), while the projections described by Villafuerte *et al.* (2020) were dynamically downscaled using RCMs; please see the details of the different approaches used in providing projections in ***Table 4.1***.

The CMIP6-derived projected changes from the CCKP described in the World Bank Group (2021) are also provided in ***Figure 4.2b***. Note that the time series of temperature anomaly values from the CCKP were computed relative to the 1995–2014 historical period. Consequently, the corresponding anomaly in observation values is shown in ***Figure 4.2b*** is noticeably smaller relative to the one shown in ***Figure 4.2a***, which was derived using the 1971–2000 baseline period. This discrepancy should be taken into consideration when comparing the recent CMIP6 projections available in CCKP with the earlier projections for the country. Thus, noting this disparity, the magnitude and trend of temperature values are comparable, with apparent similarities and proximities manifesting among certain scenarios. In particular, RCP 4.5 and RCP 8.5 have resemblances in trends and magnitudes with their SSP counterparts (i.e., SSP2-4.5 and SSP5-8.5, respectively). Also notable are the trend reversals depicted around the mid-21st century by the temperature change based on SSP1-1.9 and SSP1-2.6, indicating the net-negative emissions simulated under these scenarios (IPCC, 2021). Unanimously, among all SSP scenarios (when comparing ensemble medians), the highest projected mean temperature increase is suggested in the MAM season throughout the 21st century (see country data in the CCKP).

Figure 4.2

Annual mean temperature anomalies over the Philippines under various future climate simulation scenarios.



NOTES: (a) SRES and RCP, and (b) SSPs. Anomalies were computed relative to the (a) 1971–2000 and (b) 1995–2014 baselines. The solid black line in (a) and (b) represents the anomalies of the station observations of 1951–2015. The solid yellow lines and corresponding shadings in (a) and (b) represent the baseline mean and the 10th to 90th percentile of the ensemble range of RCP and SSP simulations, respectively; violet lines and shading in (a) denote the same for the SRES baseline. Anomaly values of projections are likewise depicted with solid lines (mean) and shadings (ensemble range) in both (a) and (b), but with distinctive colors. The dashed vertical line indicates the position of the central year of the mid-21st century time period common to the projections of different scenarios (except the SRES-A1B projection of Rahmat *et al.* (2014), which is centered at 2045).

SOURCES: (1) DOST-PAGASA (2011); (2) RAHMAT *et al.* (2014); (3) DOST-PAGASA (2018); (4) VILLAFUERTE *et al.* (2020); (5) DOST-PAGASA DATA ARCHIVE; AND (6) WORLD BANK GROUP (2021)

Under the two SSP scenarios, the projected mean temperature in the Philippines during the mid-21st century ranges from +0.5 °C to +1.6 °C (SSP2-4.5) and from +0.8 °C to +2.1 °C (SSP5-8.5). By the late 21st century, changes are shown to increase and range from +1.0 °C to +2.5 °C (SSP2-4.5) and from +2.2 °C to +4.5 °C (SSP5-8.5). These values were computed using the CMIP6 ensemble data provided by the World Bank Group (2021) through the CCKP.

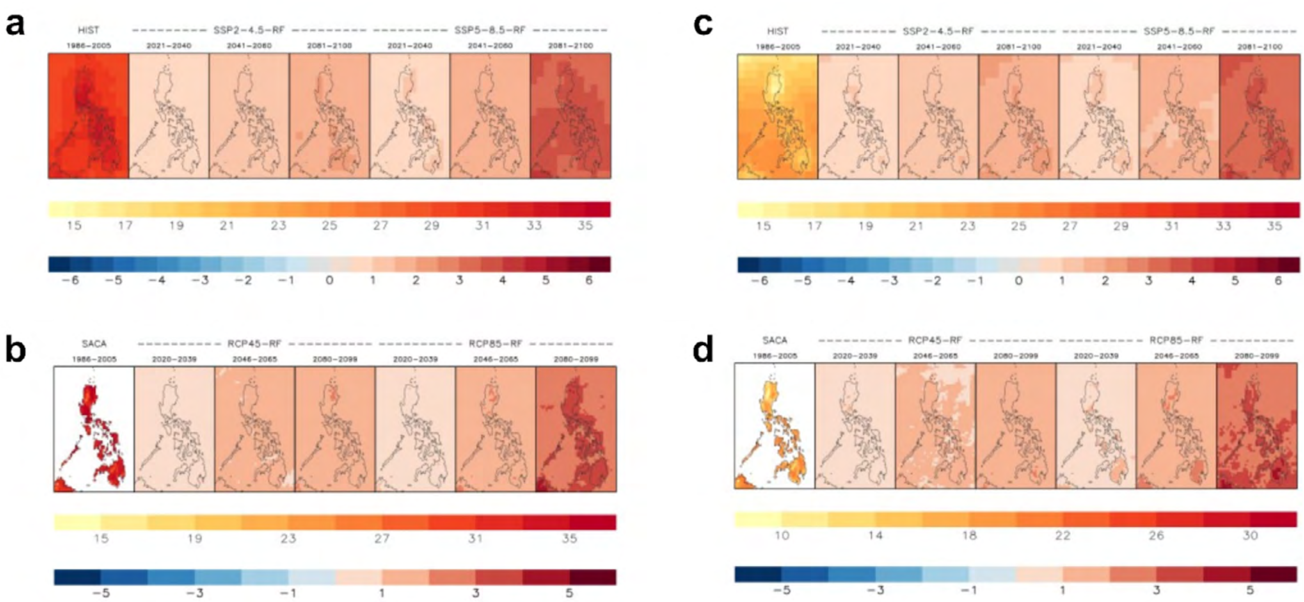
The climate extremes projections for the Philippines have also been made available for both the CMIP5 (DOST-PAGASA, MO, & ADMU, 2021) and CMIP6 simulations (World Bank Group, 2021; Gutiérrez *et al.*, 2021). As with the mean projections, there are also differences in the formulation of future extremes (e.g., the baseline or reference dataset, the ensemble size, and spatial resolution), which should be considered when comparing both datasets.

From ***Figure 4.3***, it is apparent that the change in the annual maximum of the daily maximum temperature (TXx) and the annual maximum of the daily minimum temperature (TNx) averaged over each future time slice is similar between counterpart scenarios, with a slight difference observed in both parameters between projections in the mid-21st century of SSP2-4.5 and RCP 4.5 and in the late-21st century of SSP5-8.5 and RCP 8.5. In addition, the dynamically downscaled RCP projections show portions of markedly higher temperature increases inland.

Based on the CMIP5 ensemble, the projected temperature extreme index values of the mid-21st century under RCP 4.5 concur with the earlier portrayed values of TXx and TNx (***Figure 4.4***). In particular, provincial values unanimously suggest a positive increase in magnitude with complete multi-model agreement. Meanwhile, signals vary among model outputs in the direction of change for the daily temperature range (DTR), with most of the models agreeing on increased DTR in more than 40 provinces. In terms of the frequency and duration indices for all provinces, the number of cold and cool nights is projected to decrease, while warm and hot days are shown to increase, and warm periods (or warm spells) are estimated to last longer, based on consistent signals from the ensemble members.

Figure 4.3

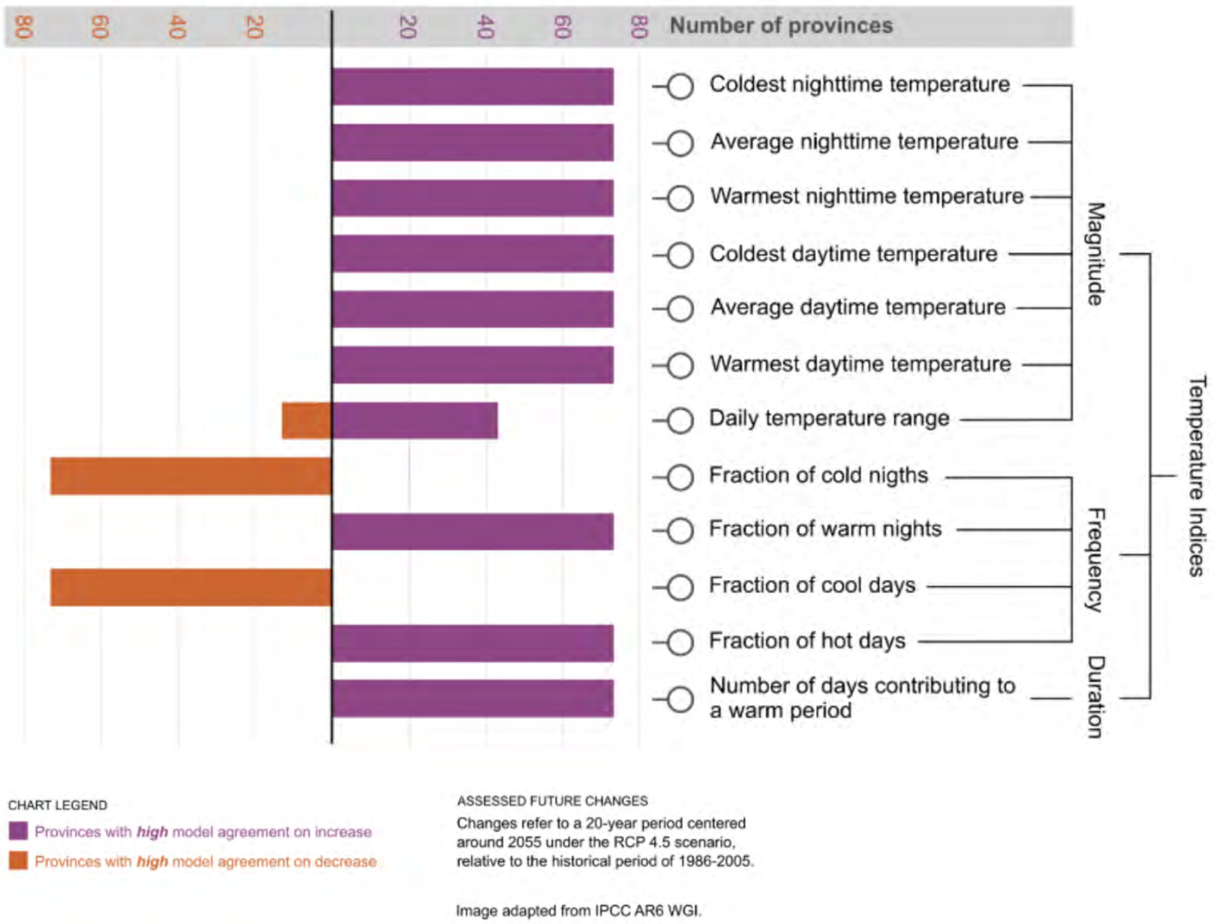
Future changes of TXx and TNx of SSP2-4.5 and SSP5-8.5 and RCP 4.5 and RCP 8.5 compared with the historical mean of the Climatic Research Unit gridded time series dataset and the Southeast Asian Climate Assessment dataset



SOURCES: DOST-PAGASA, MO, & ADMU (2021); IPCC INTERACTIVE ATLAS (GUTIÉRREZ *et al.*, 2021)

Figure 4.4

Number of Philippine provinces suggested to experience an increase (or decrease) in selected climate extreme temperature index values.



The purple (orange) bar color indicates a general increase (or decrease) in the future, while the length of the bars indicates the number of affected provinces. The contrast of the bar colors indicates a level of model agreement, with dark colors indicating high agreement (i.e., agreement among ≥ 50% simulation outputs).

SOURCE: DOST-PAGASA, MO, & ADMU (2021)

4.5 Projected Changes in Rainfall

Compared to temperature, projected changes in rainfall are more variable over geographic locations, seasons, and simulation experiments. Consequently, for the Philippines, there are remarkable differences in the seasonal mean projections under the SRES-A1B, RCP 8.5, and SSP5-8.5 (***Figure 4.5***). Climate models (both global and regional) have their inherent biases and therefore produce simulation outputs with underlying uncertainties. Thus, it is worthwhile to note the number and diversity of sources (i.e., simulation experiments) from which these projections were derived, including the size of the data pool (see Section 4.3 and ***Table 4.1***). As seen in ***Figure 4.5b*** and ***4.5c***, the ensemble means of the SSP-based and RCP-based projections have a minimal magnitude of projected changes from the baseline (i.e., ±40%). Meanwhile, the projection from SRES, which was derived from a single model source, produced a relatively larger magnitude of changes from the baseline climate (***Figure 4.5a***).

It is also notable that the large CCKP-based ensemble has a wider projection range (i.e., the difference between the 10th and 90th percentiles of the ensemble) as compared to the RCP-based projections that were produced from an ensemble of about a third of the former's size. Nevertheless, given that the SRES-based and RCP-based projections were both produced through dynamical downscaling (i.e., the influence of internal climate variability is incorporated in both datasets), these are implicitly more sensitive to the local climate.

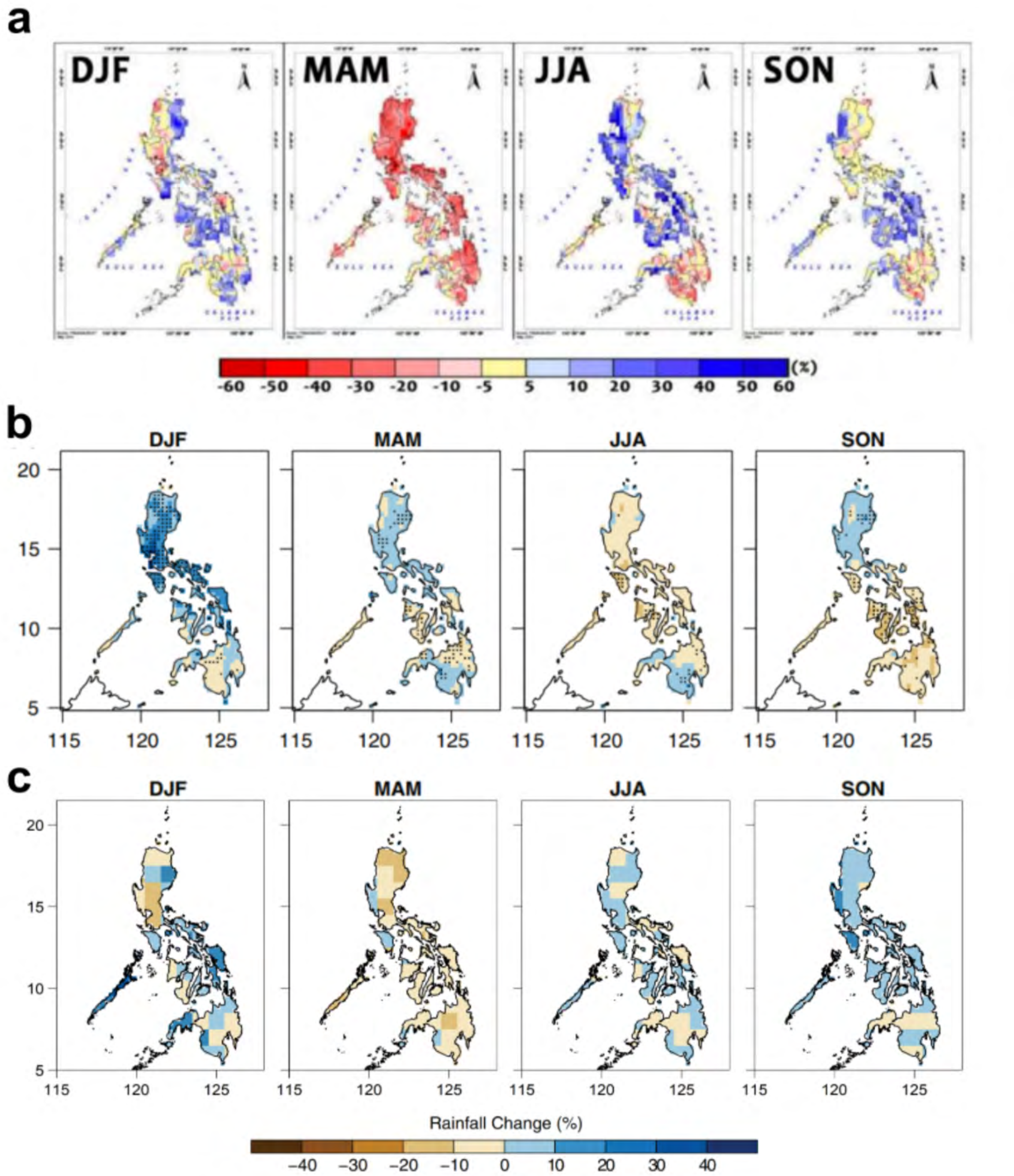
Based on the SRES-based projections, future rainfall in the mid-21st century will intensify the wet and dry periods of the Philippines, the former covering the monsoon and TC passage seasons and the latter the monsoon transition period (DOST-PAGASA, 2011; Rahmat *et al.*, 2014). However, the RCP 8.5 projections discussed by DOST-PAGASA (2018) and Villafuerte *et al.* (2020) do not conform to this pattern. For instance, in the SRES-based projections, rainfall reduction is highest during the MAM period virtually in all parts of the country; however, the multi-model mean (as well as the median) of the RCP 8.5 ensemble indicates September to November as the period with the most areas having rainfall reduction. The magnitude of these projected changes in rainfall also differs substantially between the two scenarios. Several areas of the country are projected to experience a rainfall increase (except in MAM) under SRES. Based on RCP 8.5 projections, the highest increase in rainfall over the country (specifically, over entire Luzon, most of Visayas, and certain portions of Mindanao) only occurs during December–February. The SSP5-8.5 projections (***Figure 4.5c***) agree more with the timing of the increase of SRES projections than the RCPs, although by only a smaller magnitude (within ±10%). Most notably, a predominantly drier MAM season is suggested under the SSP scenario. Furthermore, it does not coincide with the RCP 8.5 projection of longer drying over most of the Visayas region, spanning March to October, and wetter conditions in December to January over Luzon.

The suggested rainfall reduction in Mindanao is notable under RCP 8.5 and SRES, but in different seasons. The RCP 8.5 projections suggest a drying condition year-round, with the largest changes in September to February. Under SRES, however, large rainfall reduction is shown only from March to November. The SSP5-8.5 indicates widespread rainfall reduction over Mindanao in MAM, with the magnitude of reduction reaching about 20%.

As with the projected seasonal mean rainfall, apparent differences are also observable in the projections of extreme rainfall among scenarios (***Figure 4.6***). The Rx1day of the SSP-based projections shows a gradual increase in magnitude over most areas of the country across the future time slices (***Figure 4.6***). The largest increase under SSP5-8.5 (about 20%–25%) in the late 21st century is projected over western and southern Luzon, southern Visayas, and western and southeastern Mindanao.

Figure 4.5

Projected change in seasonal mean rainfall in the mid-21st century (approximately centered at 2050) under the scenarios SRES-A1B, RCP 8.5, and SSP5-8.5.



(a) SRES-A1B, (b) RCP 8.5, and (c) SSP5-8.5. Both (a) and (b) cover the time period 2036–2065, and were computed relative to the 1971–2000 baseline simulations. While (c) spans 2040–2050 and was computed relative to the 1995–2014 baseline simulations. Stiplings in (b) indicate model consensus (see details in Villafuerte *et al.*, 2020).

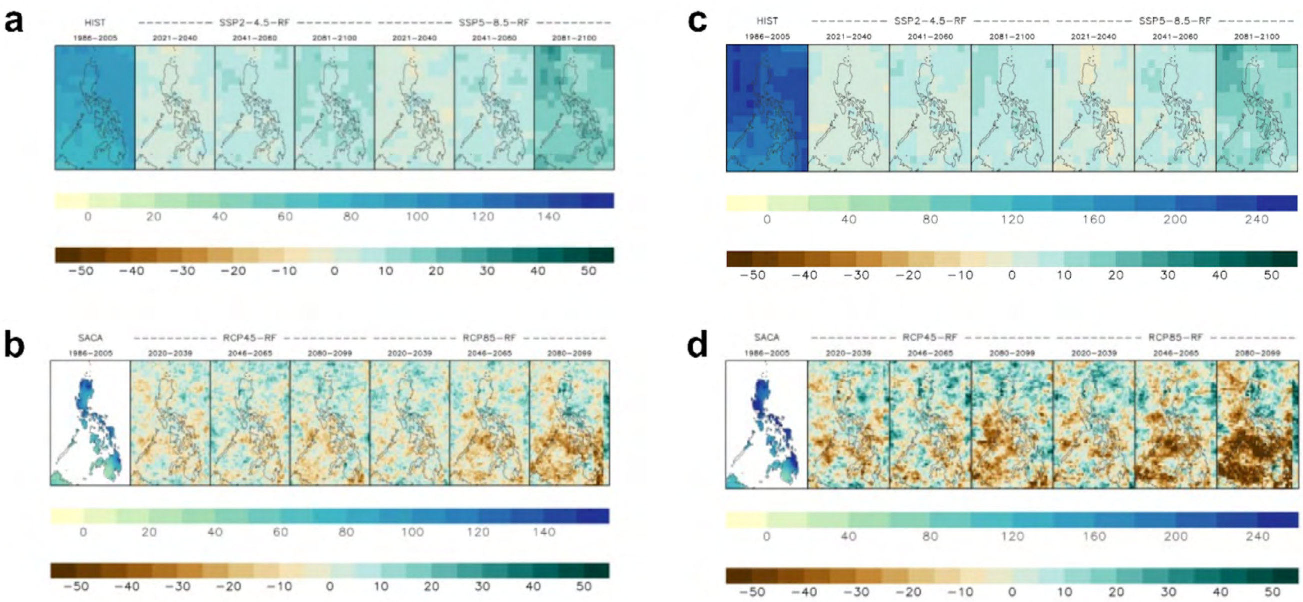
SOURCES: (A) WAS TAKEN FROM DOST-PAGASA (2011), WHILE (B) WAS TAKEN FROM VILLAFUERTE *et al.* (2020), AND (C) WAS PRODUCED USING DATA FROM THE CLIMATE CHANGE KNOWLEDGE PORTAL (WORLD BANK GROUP, 2021)

The higher-resolution, RCP-based projections are spatially diverse in terms of the direction of change, and the magnitude of changes will become more apparent by the end of the 21st century (***Figure 4.6b***). Assuming the RCP 8.5 scenario, Rx1day is expected to increase by about 20%–30% over the northern and southern parts of Luzon and slightly decrease (at about 20%) in a small portion of central Luzon. Meanwhile, most of Visayas, including Palawan and Mindoro, are projected to have a reduction (~50%) in Rx1day. For Mindanao, the suggested reduction (about 50%) in Rx1day is prevalent over the northern and eastern coasts, but slightly lower (about 40%) on the western coast and over the islands of Tawi-Tawi and Sulu. Signals of an increase, although mostly minimal, are shown in the central portion of the major islands.

The projected changes in consecutive dry days (CDD) show that the number of days with no rainfall (i.e., daily rainfall < 1.0 mm) is generally projected to increase (at most 10 days) over the eastern to central portions of Luzon and Visayas and the northeastern portion of Mindanao in both SSP scenarios (***Figure 4.6c***). There is slight variation in CDD among the future time slices of SSP2-4.5 projections, but under SSP5-8.5, the signals of increase gradually reduce, and only Luzon remains to have a noticeable change (about 6 days) by the end of the 21st century. Meanwhile, the RCP scenarios suggest minimal projected changes in CDD, with magnitudes of change of only ±2 days (***Figure 4.6d***).

Figure 4.6

Future changes of Rx1day and Rx5days of SSP2-4.5 and SSP5-8.5 and RCP 4.5 and RCP 8.5 compared with the historical mean of Climatic Research Unit gridded time series (CRU TS) dataset and Southeast Asian Climate Assessment (SACA) dataset.



(a, b) Rx1day and (c, d) Rx5days represent future changes. Upper rows display scenarios SSP2-4.5 and SSP5-8.5, while lower rows depict RCP 4.5 and RCP 8.5. Comparisons are made against the historical mean of (a, c) CRU TS dataset and (b, d) SACA dataset. Baseline maps are located on the extreme left of the maps in each panel. Each set of color bars is for the maps of historical mean (top) and future changes (bottom), in units of millimeters per day (mm/day) and percent (%), respectively.

SOURCES: DOST-PAGASA, MO, & ADMU (2021); IPCC INTERACTIVE ATLAS (GUTIÉRREZ *et al.*, 2021)

4.6 Projected Changes in Tropical Cyclones

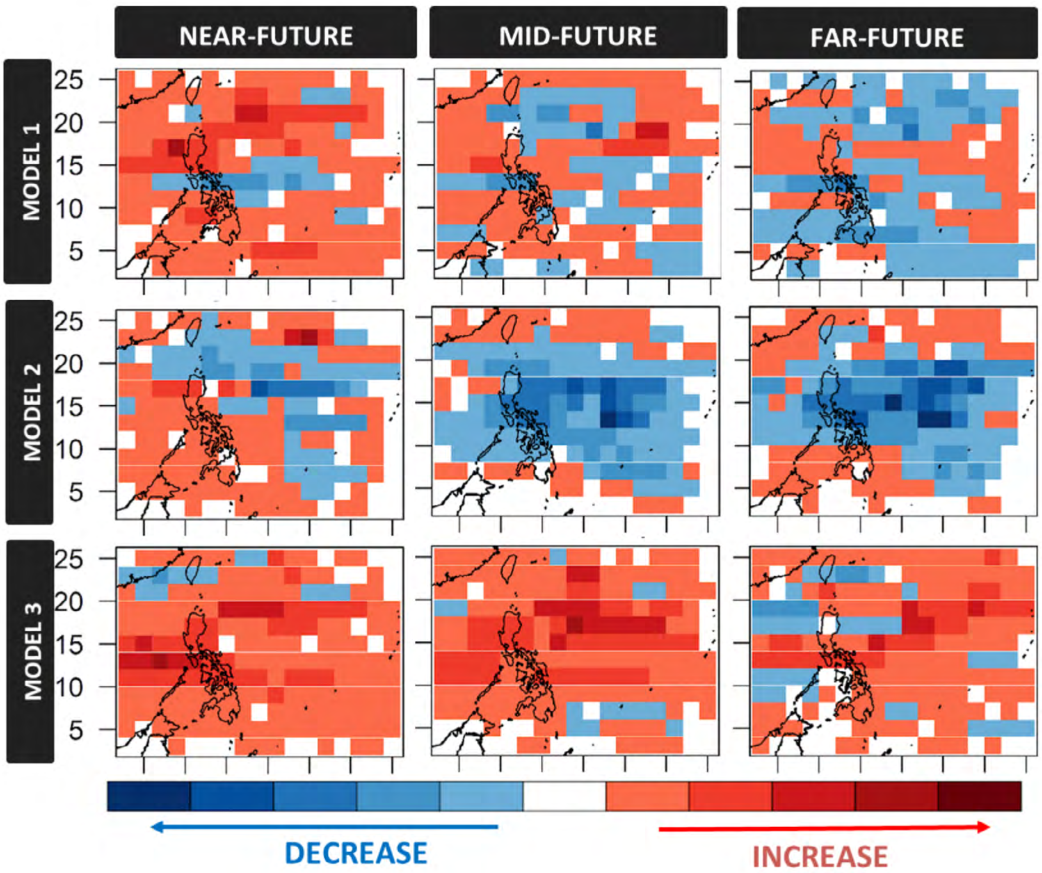
There have been recent studies on dynamically downscaled projections and historical simulations of TC activity over and around the vicinity of the Philippines (e.g., Gallo *et al.*, 2019; Tibay *et al.*, 2021; Villafuerte *et al.*, 2021). While the models were found capable of simulating TC-like vortices, they have difficulties correctly simulating the different characteristics of TCs. For instance, Gallo *et al.* (2019) obtained a low correlation coefficient ($r < 0.2$) when the time series of model-simulated and observed annual TC frequencies over the PAR were compared. TC intensities were also underestimated by the models, mainly because of many factors, including the coarse model resolution incapable of resolving sub-grid processes. The spatial distribution of TC-associated rainfall is also not well represented in the models (e.g., Villafuerte *et al.*, 2021).

Despite the difficulties of the models in capturing the observed TC characteristics, a few advancements have been achieved in modeling TCs that were not done in the earlier assessment. Hence, it is worth reporting here what has been done on the projected future changes in TCs. CMIP5-downscaled projections shown in Gallo *et al.* (2019) indicate a slight decrease in the number of TCs to affect the Philippines by the mid-21st century. The projections further reveal that while TCs affecting the country are expected to be slightly fewer, they are projected to be more intense in the future.

It has also been recognized that the confidence in model projections for TCs is low, particularly in providing spatial information, given the disagreement among the models' projected changes in TCs. As an example, spatial maps of the simulated future change in TC frequency for a two-degree by two-degree grid box are shown in ***Figure 4.7***. One model projects an increase in TC activity over some areas, while the other model provides the opposite signal. Given these limitations in the projected values, Gallo *et al.* (2019) suggest that for future planning horizons, it is important to consider the high year-to-year variability and the highly damaging effects of TCs, which have been observed historically in the country.

Figure 4.7

Comparison of projected changes in tropical cyclone frequency at every 2°×2° grid box based on three dynamically downscaled climate model simulations covering three different future time periods.



SOURCE: VILLAFUERTE (N.D.)

4.7 Challenges and Directions for Future Studies

There has been significant progress in climate projections for the Philippines since the previous PhilCCA Report in 2016. From the single model-based projections of the SRES scenarios (e.g., DOST-PAGASA, 2011; Rahmat *et al.*, 2014), recent collaborative work from many institutions across Southeast Asia and around the world has enabled researchers access to multiple dynamically downscaled model simulations over the Philippines (e.g., Villafuerte *et al.*, 2020; Tangang *et al.*, 2021), resulting in a much more robust dataset from which climate projections may be derived. In addition, statistically downscaled climate projections (e.g., Fick & Hijmans, 2017) have also allowed further investigation of local climate change (e.g., Basconcillo *et al.*, 2016; Salvacion, 2017).

In addition to providing projections of the mean climate (DOST-PAGASA, 2018), projections of climate extremes at 25 km resolution and aggregated to the provincial level have also been produced (DOST-PAGASA, MO, & ADMU, 2021). These datasets have been the basis for local government units (LGUs) to prepare their Local Climate Change Action Plans (LCCAP) through the Climate and Disaster Risk Assessment (CDRA) process.

The most recent IPCC report also provides user-friendly access to the CMIP6 dataset via the IPCC Interactive Atlas. Aside from regional-level information, the Atlas also allows global projected data to be downloaded from the ensemble of CMIP6 models, thus allowing users to look at specific countries at about 50-km resolution. Other organizations, such as the World Bank and Asian Development Bank, have developed complementary web sites (e.g., the CCKP; World Bank Group, 2021), which provide country-level climate projection data. The WorldClim (Fick & Hijmans, 2017) also provides statistically-downscaled CMIP6 data for individual models and multiple scenarios for selected climate variables. The downscaled data is available at several horizontal resolutions, ranging from 10 minutes (~20 km) to as fine as 30 seconds (~1 km). CHELSA (Karger *et al.*, 2020) likewise provides ~5 km horizontal resolution of climate projections from selected CMIP6 GCMs and scenarios.

A summary of currently available downscaled climate projection datasets is provided in ***Table 4.1***. A more detailed version of this table listing the methodologies, assumptions, uncertainties, and quality of different data products, as suggested by Darron *et al.* (2018), is provided in the supplementary materials.

Despite these improvements, however, there are still limitations in the existing downscaled model projections, which need to be addressed when preparing the new set of projections from the CMIP6 dataset. These include the computationally demanding tasks of producing dynamically downscaled CMIP6 projections for the Philippines.

4.7.1 *Model Biases and Uncertainty*

Tangang *et al.* (2021) noted that while the implementation of multi-model downscaling projects such as CORDEX SEA has been generally successful, model bias and uncertainty are priority issues that need to be addressed. Biases need to be addressed not just by selecting the "good" GCMs, which are capable of simulating the mean climate and variability in the region, but also by optimizing the parameterizations used by RCMs. A model intercomparison for simulating climate in Southeast Asia has been recommended and is ongoing.

For regions with complex topography and coastlines, including many small islands such as the Philippines, the 25-km resolution provided by the RCMs is still not enough to capture the local climate. Initial work (e.g., Ngai *et al.*, 2020) indicates improvements in simulation by increasing the resolution to 5 km, particularly in terms of extreme precipitation. However, increasing the resolution to 5 km puts the RCM simulation within the "gray zone," a resolution just beyond the 4 km or less used by Convective Permitting Models (CPM; Prein *et al.*, 2015). The use of CPMs in complex regions, such as the Philippines, may improve simulations of convective processes.

The use of regional models with coupled atmosphere–ocean–land components could further improve simulations in the region. This is in comparison to the current uncoupled models, where the atmosphere is simply forced by SST and not allowed to provide feedback to the ocean. Initial work using such models has indicated improvement and reduced bias in simulating climate (Primo *et al.*, 2019).

Model biases can translate into uncertainty (an increased range of values) in projections, which makes decision-making in climate change adaptation difficult. While the robustness of the climate change signals may be determined in terms of model agreement, the cost of downscaling also limits the number of future scenarios available to users. The use of single scenarios can result in non-robust adaptation recommendations, given the likelihood of future events deviating from this single scenario. A compromise method of using a small subset of future scenarios (e.g., median, best, and worst case) to obtain a relevant range of outputs may be done instead of using a full set of future climate scenarios (Darron *et al.*, 2018).

4.7.2 *Observational Datasets*

While statistical downscaling methods are typically good over the historical period (as they are based on observations), they also require a sufficiently high-density observation network with reliable and high-quality data over space and time. Observation data are likewise valuable for bias correction to obtain realistic absolute values of relevant climate variables (Darron *et al.*, 2018).

Unfortunately, this observation network is still not dense enough for the Philippines, where most stations are located in or near urban or coastal plains, with limited observations over remote, rural, and mountainous areas (see, e.g., Villafuerte *et al.*, 2021). Long-term (historical), high-frequency (daily and sub-daily), and updated climate observation data are still difficult to obtain or unavailable (i.e., still in need of digitization or data rescue from historical archives). These daily and sub-daily data are important for the analysis of climate extremes. And while long-term historical observations are important for validating model simulations, updated observational data are also valuable for monitoring how well previous projections have simulated the present climate.

Marine and ocean data are likewise unavailable or inaccessible. The lack of observation data over the marine environment has limited the use of model data over coastal regions, as the climate variables in these areas cannot be validated using in situ observations. In such cases, reanalysis data (e.g., ERA-40 and JRA-55) are used to compare with model simulations.

4.7.3 *Distillation*

Climate projections alone are insufficient information to fully understand the potential impacts of climate change and inform climate adaptation choices; detailed impact assessments (at the temporal and spatial resolution required for decision-making) are also important (Darron *et al.*, 2018).

Climate risk and impact assessment tools may include matrices such as the Climate Information Risk Analysis (CliRAM) (DOST-PAGASA, 2018) and Climate Extremes Risk Analysis Matrix (CERAM) (DOST-PAGASA *et al.*, 2021), as well as more complex impact models such as those used for crop modeling (e.g., Kephe *et al.*, 2021), renewable energy production (e.g., Seljom *et al.*, 2011), and water resources management (e.g., Tolentino *et al.*, 2016). These risk assessment tools and impact models vary in complexity, but they all require climate data as input and typically have far more stringent data requirements than are needed for general communications and climate risk analysis (Daron *et al.*, 2018). These could include realistic, internally consistent datasets of climate variables such as temperature, precipitation, evaporation, and solar radiation at finer spatial (barangay or farm-scale) and temporal (daily or even hourly) resolutions than are currently provided by RCMs. Thus, existing downscaled climate projection data may still not meet the needs of users. Both climate information providers and users, including the impacts and adaptation (VIA) communities and policymakers, will need to work together to overcome this challenge.

Other stakeholders who have access to other resources (e.g., computing platforms, observation networks, risk analysis, socio-economic tools, business opportunities, and others) who can contribute to the different aspects of climate change adaptation and mitigation should also take part in co-creating climate policies.

Indeed, emerging studies show that engaging stakeholders is as important as the climate information itself (Jack *et al.*, 2021). In the Philippines, climate information is gradually being introduced to policymakers through the CDRA process as LGUs create their LCCAP. Other non-government, humanitarian, and development organizations and private organizations are likewise starting to use these climate projections. However, a tighter collaboration between different players and the co-creation of climate information would be beneficial to both climate information providers, decision-makers, and the rest of the community.

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This second cycle of the Philippine Climate Change Assessment (PhilCCA) is an update to the initial reports first published in 2016. It synthesizes scientific information from 2016 onwards, providing a comprehensive review and assessment of the state of knowledge on climate change science and impacts in the Philippines. Modeled after the global assessment reports of the Intergovernmental Panel on Climate Change, the PhilCCA offers a thorough analysis of available local and international literature to enhance understanding and inform decision-making.

The PhilCCA Reports are organized into three volumes:

- Working Group 1: *The Physical Science Basis*
- Working Group 2: *Impacts, Adaptation, and Vulnerability*
- Working Group 3: *Mitigation of Climate Change*

This volume by Working Group 1 focuses on the physical science basis of climate change. It presents the latest research on the physical mechanisms driving climate in the Philippines and the potential local effects of increased greenhouse gas levels.

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