

The Ocean and Cryosphere in a Changing Climate

Special Report of the Intergovernmental Panel on Climate Change

Edited by

Hans-Otto Pörtner

Working Group II Co-Chair

Debra C. Roberts

Working Group II Co-Chair

Valérie Masson-Delmotte

Working Group I Co-Chair

Panmao Zhai

Working Group I Co-Chair

Melinda Tignor

Head of WGII TSU

Elvira Poloczanska

Science Advisor to the WGII
Co-Chairs and TSU

Katja Mintenbeck

Director of Science

Andrés Alegría

Graphics Officer

Maike Nicolai

Communications Officer

Andrew Okem

Science Officer

Jan Petzold

Science Officer

Bardhyl Rama

Director of Operations

Nora M. Weyer

Science Officer

Working Group II Technical Support Unit



University Printing House, Cambridge CB2 8BS, United Kingdom
One Liberty Plaza, 20th Floor, New York, NY 10006, USA
477 Williamstown Road, Port Melbourne, VIC 3207, Australia
314–321, 3rd Floor, Plot 3, Splendor Forum, Jasola District Centre, New Delhi – 110025, India
103 Penang Road, #05-06/07, Visioncrest Commercial, Singapore 238467

Cambridge University Press is part of the University of Cambridge.
It furthers the University's mission by disseminating knowledge in the pursuit of education,
learning, and research at the highest international levels of excellence.

www.cambridge.org
Information on this title: www.cambridge.org/9781009157971
DOI: 10.1017/9781009157964

© Intergovernmental Panel on Climate Change 2022

This work is in copyright. It is subject to statutory exceptions and to the provisions of relevant licensing agreements; with the exception of the Creative Commons version the link for which is provided below, no reproduction of any part of this work may take place without the written permission of Cambridge University Press.

An online version of this work is published at doi.org/10.1017/9781009157964 under a Creative Commons Open Access license CC-BY-NC-ND 4.0 which permits re-use, distribution and reproduction in any medium for non-commercial purposes providing appropriate credit to the original work is given. You may not distribute derivative works without permission. To view a copy of this license, visit <https://creativecommons.org/licenses/by-nc-nd/4.0>

All versions of this work may contain content reproduced under license from third parties.
Permission to reproduce this third-party content must be obtained from these third-parties directly.

When citing this work, please include a reference to the DOI 10.1017/9781009157964

First published 2022

Printed in the United Kingdom by TJ Books Limited, Padstow Cornwall

A catalogue record for this publication is available from the British Library.

ISBN 978-1-009-15797-1 Paperback

Cambridge University Press has no responsibility for the persistence or accuracy of URLs for external or third-party internet websites referred to in this publication and does not guarantee that any content on such websites is, or will remain, accurate or appropriate.

This report should be cited as:

IPCC, 2019: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 755 pp.
<https://doi.org/10.1017/9781009157964>.

The designations employed and the presentation of material on maps do not imply the expression of any opinion whatsoever on the part of the Intergovernmental Panel on Climate Change concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries.

Front and back cover artwork and layout by Stefanie Langsdorf

Contents

Front Matter	Foreword	vii
	Preface	ix
SPM	Summary for Policymakers	3
TS	Technical Summary	39
Chapters	Chapter 1 Framing and Context of the Report	73
	Chapter 2 High Mountain Areas	131
	Chapter 3 Polar Regions	203
	Chapter 4 Sea Level Rise and Implications for Low-Lying Islands, Coasts and Communities	321
	Chapter 5 Changing Ocean, Marine Ecosystems, and Dependent Communities	447
	Chapter 6 Extremes, Abrupt Changes and Managing Risks	589
Cross-Chapter Box	Cross-Chapter Box 9 Integrative Cross-Chapter Box on Low-lying Islands and Coasts	657
Annexes	Annex I Glossary	677
	Annex II Acronyms	703
	Annex III Contributors to the IPCC Special Report on the Oceans and Cryosphere in a Changing Climate	707
	Annex IV Expert Reviewers of the IPCC Special Report on the Oceans and Cryosphere in a Changing Climate	717
	Index	739



Foreword and Preface

Foreword

This *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* (SROCC), is the third Special Report to be produced in the Intergovernmental Panel on Climate Change's (IPCC) Sixth Assessment Report (AR6) cycle. SROCC is unique because – for the first time – the IPCC has produced an in-depth report examining the farthest corners of the Earth – from the highest mountains and remote polar regions to the deepest oceans. The report finds that even and especially in these places, human-caused climate change is evident. These changes show that the world's ocean and cryosphere have been 'taking the heat' for climate change for decades. The consequences for nature and humanity are sweeping and severe. This report highlights the urgency of timely, ambitious, coordinated, and enduring action.

SROCC was jointly prepared by Working Groups I and II, and provides the latest state of knowledge on the ocean and cryosphere in a changing climate. It focuses on changes to mountain cryosphere, polar regions and ecosystems, sea level rise and coastal extremes, ocean and marine life, as well as providing key information to enable action at all scales and to manage risks and build resilience through adaptation for the benefit of ecosystems and human societies. The report highlights the observed and projected changes in the ocean and cryosphere, the associated impacts and risks for human societies and ecosystems, as well as assessing a range of response options and adaption measures. SROCC clearly presents the level of risks and the limits of adaptation for high emission scenarios and thereby the benefits of ambitious and effective adaptation for sustainable development. It highlights the importance of irreversible and committed changes on timescales of decades to centuries. It stresses the urgency of near-term action to reduce risks also by reducing emissions of greenhouse gases, strengthening findings from the SR15 and SRCCL reports.

The IPCC provides policymakers with regular scientific assessments on climate change, its impacts and risks, as well as adaptation and mitigation options. Since it was established jointly in 1988 by the World Meteorological Organisation and the United Nations Environment Programme, the IPCC has produced a series of Assessment Reports,

Special Reports, Technical Papers and Methodological Reports and other products that have become the gold standard scientific resource on climate change issues for policymakers.

SROCC was made possible thanks to the commitment and dedication of hundreds of experts worldwide, representing a wide range of disciplines. We express our deep gratitude to all Coordinating Lead Authors, Lead Authors, Contributing Authors, Review Editors, Chapter Scientists and Expert and Government Reviewers who devoted their time and effort to make the Special Report on the Ocean and Cryosphere in a Changing Change possible. We would like to thank the staff of the Working Group Technical Support Units and the IPCC Secretariat for their dedication and professionalism.

We are also grateful to the governments that supported their scientists' participation in developing this report and that contributed to the IPCC Trust Fund to provide for the essential participation of experts from developing countries and countries with economies in transition. We would like to express our appreciation to the Principality of Monaco for hosting the SROCC Scoping Meeting, to the Governments of Fiji, Ecuador, China, and the Russian Federation for hosting Lead Author Meetings, and to the Principality of Monaco for hosting the Second Joint Session of Working Group I and Working Group II. Our thanks also to the Government of France for funding the Technical Support Unit of Working Group I, and to the Government of Germany and the Governments of Norway and New Zealand, for funding the Technical Support Unit of Working Group II. We also acknowledge the Government of Norway's generous contribution in support of the development of the graphics for SROCC Summary for Policymakers, and the support of the Prince Albert II of Monaco Foundation and the Fondation de France for an additional post in the Working Group II Technical Support Unit.

We especially wish to thank the IPCC Chair, Hoesung Lee, the IPCC Vice-Chairs Ko Barrett, Thelma Krug, and Youba Sokona for their guidance, and the Co-Chairs of Working Groups II and I Hans-Otto Pörtner, Debra Roberts, Valérie Masson-Delmotte and Panmao Zhai for their inspired leadership throughout the process.



Petteri Taalas
Secretary-General
World Meteorological Organisation



Inger Andersen
Executive Director
United Nations Environment Programme

Preface

This IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC), is the third Special Report to be produced in the Intergovernmental Panel on Climate Change's (IPCC) Sixth Assessment Report (AR6) cycle. Its findings reinforce those of the two earlier Special Reports, the IPCC Special Report on Global Warming of 1.5°C and the IPCC Special Report on Climate Change and Land. The report was jointly prepared by Working Groups I and II, with the Working Group II Technical Support Unit leading the operational production. It was prepared following IPCC principles and procedures. This Special Report builds upon the IPCC's Fifth Assessment Report (AR5) in 2013–2014 and on relevant research published in the scientific, technical and socio-economic literature. The report sits alongside other related reports from other UN Bodies, including Intergovernmental Science Policy Platform on Biodiversity and Ecosystem Services (IPBES) Global Assessment Report on Biodiversity and Ecosystem Services.

Scope of the Report

The IPCC SROCC responds to proposals for Special Reports from governments and observer organisations provided at the start of the IPCC AR6 cycle. It assesses the observed and projected changes to the ocean and cryosphere and their associated impacts and risks, with a focus on resilience, risk management response options, and adaptation measures, considering both their potential and limitations. SROCC brings together knowledge on physical and biogeochemical changes, the interplay with ecosystem changes, and the implications for human communities. The report was produced with careful attention to other assessments, with the aim of achieving coherence and complementarity, as well as providing an updated assessment of the current state of knowledge. The Special Report considered literature accepted for publication up to 15 May 2019.

Structure of the Report

This report consists of a short Summary for Policymakers, a Technical Summary, six Chapters, an Integrative Cross-Chapter Box, four Annexes, as well as online Supplementary Material.

Chapter 1: Framing and Context introduces the reader to the structure of the report and the content presented in more detail in subsequent chapters. It highlights the role of the ocean and cryosphere in the Earth system, assessment of climate impacts and future risks for ecosystems and human societies from the high mountains to the deep ocean, the knowledge systems informing responses to climate change, as well as the capacities of governance and institutions to implement such responses, and it highlights key concepts and terms as well as linkages between chapters.

Chapter 2: High Mountain Areas provides a wide-ranging assessment of the observed and projected cryosphere (including snow, glaciers, permafrost, lake and river ice) changes in high mountain areas, as well as associated impacts, risks, and adaptation measures related to natural and human systems.

Chapter 3: Polar Regions presents the state of knowledge concerning changes in the Arctic and Antarctic oceans and marine and land cryosphere, how they are affected by climate change, and projections for the future. It assesses impacts of individual and interacting polar system changes, as well as response options to reduce risk and build resilience in the polar regions.

Chapter 4: Sea Level Rise and Implications for Low-lying Islands, Coasts and Communities assesses past and future contributions of various processes to global, regional and extreme sea level changes, the associated risks, and response options and pathways to resilience and sustainable development.

Chapter 5: Changing Ocean, Marine Ecosystems, and Dependent Communities focuses on observations of climate-related trends, impacts and adaptation, projected changes and associated risks, as well as the response options to enhance resilience.

Chapter 6: Extremes, Abrupt Changes and Managing Risks assesses extreme as well as abrupt or irreversible changes in the ocean and cryosphere including recent anomalous extreme events, compound risk, cascading effects, their impacts on human and natural systems, and sustainable and resilient risk management strategies.

Finally, the *Integrative Cross-Chapter Box on Low-Lying Islands and Coasts* highlights the key assessment findings relating to low lying islands and coasts. It includes summary information on the critical climate-related drivers, their observed and projected impacts on related geographies and major sectors, and responses, including adaptation strategies in practice.

The Process

The IPCC SROCC was prepared in accordance with the principles and procedures established by the IPCC and represents the combined efforts of leading experts in the field of climate change. A scoping meeting for SROCC was held in Monaco in December 2016, and the final outline was agreed by the Panel at its 45th Session in March 2017 in Guadalajara, Mexico. Governments and IPCC observer organisations nominated more than 500 experts for the chapter team. The team of 14 Coordinating Lead Authors, 75 Lead Authors, and 15 Review Editors were selected by Working Groups I and II Bureaux. In addition, 222 Contributing Authors were invited by the chapter teams to provide scientific and technical information in the form of text, graphs or data. The report drafts prepared by the authors were subject to two rounds of formal review and revision followed by a final round of government comments on the Summary for Policymakers. The enthusiastic participation of the scientific community and governments to the review process resulted in over 31,000 written review comments, submitted by 824 expert reviewers and 43 governments. The Review Editors for the chapters monitored the review process to ensure that all substantive review comments received appropriate consideration. The Summary for Policymakers was approved at the Second Joint Session of Working Groups I and II, and the Summary for Policymakers

Preface

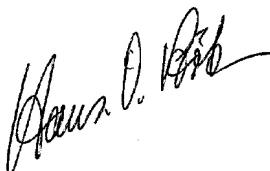
and the underlying chapters were then accepted by the IPCC at its 51st Session in September 2019 in Monaco.

Acknowledgements

We express our deepest appreciation for the expertise and commitment shown by the Coordinating Lead Authors and Lead Authors throughout the process. They were ably helped by the many Contributing Authors who served on SROCC. The Review Editors were critical in assisting the author teams and ensuring the integrity of the review process. We are grateful to the Chapter Scientists who supported the chapter teams in the delivery of the report. We would also like to thank all the expert and government reviewers who submitted comments on the drafts.

The production of the report was guided by members of the IPCC Bureau. We would like to thank our colleagues who supported and advised us in the development of the report: Working Group I Vice-Chairs Edvin Aldrian, Fatima Driouech, Gregory Flato, Jan Fuglestvedt, Muhammad I. Tariq, Carolina Vera, Noureddine Yassaa; Working Group II Vice-Chairs Andreas Fischlin, Mark Howden, Carlos Méndez, Joy Jacqueline Pereira, Roberto A. Sánchez-Rodríguez, Sergey Semenov, Pius Yanda, and Taha M. Zatari; and Working Group III Vice-Chair Amjad Abdulla. Our appreciation also goes to Ko Barrett, Vice Chair of IPCC, who served as champion for the report and ably supported us from scoping through approval.

Our sincere thanks go to the hosts and organizers of the Scoping Meeting, the four Lead Author Meetings, and the Joint Working Group and IPCC Sessions. We gratefully acknowledge the support from the Principality of Monaco and the Prince Albert II of Monaco Foundation, the Government of Fiji and the University of the South Pacific, the Government of Ecuador, the Government of China and the Chinese Academy of Sciences, the Government of the Russian Federation and Kazan Federal University, and the Principality of Monaco and the Prince Albert II of Monaco Foundation. The support provided by many governments as well as through the IPCC Trust Fund for the many experts participating in the process is also noted with appreciation.



Hans-Otto Pörtner
IPCC Working Group II Co-Chair



Valérie Masson-Delmotte
IPCC Working Group I Co-Chair

The staff of the IPCC Secretariat based in Geneva provided a wide range of support for which we would like to thank Abdalah Mokssit, Secretary of the IPCC, and his colleagues: Kerstin Stendahl, Jonathan Lynn, Sophie Schlingemann, Jesbin Baidya, Laura Biagioli, Annie Courtin, Oksana Ezkarkho, Judith Ewa, Joelle Fernandez, Andrea Papucides Bach, Nina Peeva, Mxolisi Shongwe, and Werani Zabula. Thanks are due to Elhouisseine Gouaini and Adriana Oskarsson who served as the conference officers for the 51st Session of the IPCC.

The report production was managed by the Technical Support Unit of IPCC Working Group II, through the generous financial support of the German Federal Ministry for Education and Research and the Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research. The Prince Albert II of Monaco Foundation and the Fondation de France provided financial support for a scientific staff member to the Working Group II Technical Support Unit, while the Norwegian Environment Agency enabled additional graphics support for the Summary for Policymakers. Additional funding from the Governments of Norway and New Zealand support the Working Group II Technical Support Unit office in Durban, South Africa. Without the support of all these bodies this report would not have been possible.

This report could not have been prepared without the dedication, commitment, and professionalism of the members of the Working Group II Technical Support Unit: Melinda Tignor, Elvira Poloczanska, Katja Mintenbeck, Andrés Alegría, Marlies Craig, Anka Freund, Stefanie Langsdorf, Philisiwe Manqele, Maike Nicolai, Andrew Okem, Jan Petzold, Bardhyll Rama, Jussi Savolainen, Stefan Weisfeld, Nora Weyer, and Mallou. Our warmest thanks go to the collegial and collaborative support provided by Sarah Connors, Melissa Gomis, Robin Matthews, Clotilde Péan, Anna Pirani, and Rong Yu from the WGI Technical Support Unit, and Katie Kissick from the WGIII Technical Support Unit. In addition, the following contributions are gratefully acknowledged: Martin Künsting (graphics support for the Summary for Policymakers), David Dokken (approval session support), Naomi Stewart (copyedit), Marilyn Anderson (index), and Soapbox (layout).

And a final, special thank you to the colleagues, family and friends who supported us through the many long hours and days spent at home and away from home while producing this report.



Debra C. Roberts
IPCC Working Group II Co-Chair



Panmao Zhai
IPCC Working Group I Co-Chair