

Climate Change 2021

The Physical Science Basis

Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change

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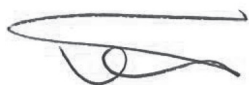
Foreword, Preface and Dedication

Foreword

It is unequivocal that human activities have heated our climate. Recent changes are rapid, intensifying, and unprecedented over centuries to thousands of years. With each additional increment of warming, these changes will become larger, resulting in long-lasting, irreversible implications, in particular for sea level rise. United Nations Secretary-General António Guterres has stated that 'the evidence is irrefutable' and 'we see the warning signs in every continent and region'.

The Working Group I contribution to the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report provides a reality check on climate change. We now have a much clearer picture of the past, present and possible future climates, and this information is essential for understanding where we are headed, what can be done, and the multiple facets of a changing climate to prepare for, in every region. Unless deep reductions in greenhouse gas emissions occur in the coming decades, global warming of 1.5°C and 2°C above pre-industrial levels will be exceeded during the 21st century.

The new Working Group I Report structure integrates multiple lines of scientific evidence within each chapter and provides robust knowledge relevant for policymaking through the end-to-end assessment of key topics. This more holistic approach has resulted in a report that provides a better understanding of the climate system, for both past and future changes, with a new emphasis on climate information for regions, which is critical for informing adaptation and risk management strategies. Today, many decisions remain grounded in the experience of past climate variability. This report provides a solid basis for taking into account future changes that need to be considered in today's decisions, with increased relevance for climate services, to enhance adaptation and resilience to climate change and curb greenhouse gas emissions.



Petteri Taalas
Secretary-General
World Meteorological Organization

The journey of this report reflects extraordinary efforts by all contributors under exceptional circumstances. The COVID-19 pandemic, which started during the review of the Second Order Draft, disrupted the process. However, the early response of Working Group I, through the hard work of the authors, review editors, chapter scientists, the Technical Support Unit, and Bureau members, made it possible to deliver a report that meets the most stringent science quality standards, thanks to the in-depth, broad review process, with an exhaustive, robust, rigorous and transparent assessment of the latest state of climate science knowledge. We commend the additional efforts taken, including by all reviewers from the research community and government representatives who adapted to a new way of working to complete this vital report. Our particular appreciation goes to the Working Group I Co-Chairs Valérie Masson-Delmotte and Panmao Zhai for their leadership throughout the process. Their extraordinary efforts ensured that this robust and clear report is available to the world today.

This Working Group I contribution to the IPCC's Sixth Assessment Report covers important new advances in climate science that provide an invaluable input into climate negotiations and decision-making, with an emphasis on key conditions that, from a physical science basis, are needed to limit global warming and inform risk assessment and regional adaptation. The report was welcomed at the 26th Conference of the Parties to the United Nations Framework Convention on Climate Change. It will also inform the 2023 global stocktake. Unless there are deep reductions in global greenhouse gas emissions, the goal of limiting warming well below 2°C and close to 1.5°C will be out of reach.

The science is unequivocal, the changes are unprecedented, and there is no more time for delay.



Inger Andersen
Executive Director
United Nations Environment Programme

Preface

The Working Group I (WGI) contribution to the Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC) focuses on a full and comprehensive assessment of the physical science basis of climate change, based on evidence from more than 14,000 scientific publications available by 31 January 2021.

This Report reflects recent climate science advances resulting from progress in, and the integration of, multiple lines of evidence, including: in situ and remote observations; paleoclimate information; understanding of climate drivers and physical, chemical and biological processes and feedbacks; and global and regional climate modelling; as well as advances in methods of analyses and insights from the growing field of climate services.

The AR6 WGI Report builds on the WGI contribution to the IPCC's Fifth Assessment Report (AR5) in 2013, and the AR6 Special Reports¹ released in 2018 and 2019.

The report considers the current state of the climate in the long-term context, the understanding of human influence, the state of knowledge about possible climate futures, climate information relevant for climate-related risk assessment and regional adaptation, and the physical science basis on limiting human-induced climate change.

Scope of the Report

As part of the scoping process and approval of the outline of the IPCC Sixth Assessment Report, the WGI contribution evolved from the structure of past WGI assessment reports, reflecting developments in climate science and the assessment of global and regional climate information that is relevant to inform decision-making.

Some key new topics assessed by WGI include the global response to new illustrative emissions scenarios, physical climate storylines, low-likelihood, high-impact outcomes, and physical climate conditions that affect society and/or ecosystems (defined as climatic impact-drivers).

The integration of multiple lines of evidence strengthens the understanding of past, current and possible future changes in the climate system and the distillation of regional climate change information at regional scale. The new structure of the WGI Report is designed to facilitate this integration for end-to-end assessment of key topics and to enhance the visibility of knowledge developments for global and regional climate change. This includes climate information that is relevant for risk assessment, regional adaptation and for mitigation. It is also designed to inform decision-making

without being policy prescriptive and to facilitate the integration of the WGI key findings with the other AR6 Working Group reports.

Structure of the Report

This Report consists of thirteen thematic chapters with their supporting supplementary material, ten annexes (including the report Glossary, which is developed in coordination with Working Groups II and III where relevant), an integrative Technical Summary, and a Summary for Policymakers. An innovation in this Working Group I assessment is the online Interactive Atlas (<https://interactive-atlas.ipcc.ch>), a novel tool for flexible spatial and temporal analyses of observed and projected climate change information, which enhances accessibility for stakeholders and users to the data assessed in the Report.

The Summary for Policymakers and Technical Summary include the line of sight, indicated in curly brackets, to the chapters and the specific sections therein where the detailed assessment can be found. In this way, these summary components of the Report provide a roadmap to the contents of the entire report and a synthesis of the major findings that is traceable to the underlying literature and assessment.

The introduction (Chapter 1) of the Report frames the WGI assessment within the broader AR6 and global climate policy context and introduces the key concepts, lines of evidence, and major developments. The remainder of the Report is structured in three segments. The first segment focuses on large-scale climate change (Chapters 2–4). These chapters provide an updated and comprehensive assessment of knowledge about the current state of the climate system, human influence and projections of future change on key large-scale indicators of the climate system. Chapter 2 assesses observed large-scale changes in the climate system in the long-term paleoclimate context. Chapter 3 updates the assessment of human influence on the climate system, considering natural variability, model performance and detection and attribution. Chapter 4 covers global climate projections spanning time horizons from the near term (2021–2040) to the mid-term (2041–2060), long term (2081–2100) and beyond.

The second segment of the report is dedicated to climate system components and processes that play key roles in global and regional climate (Chapters 5–9), including carbon and other biogeochemical cycles, energy, and water; short-lived climate forcers (SLCFs) and their link to air quality; and changes in the ocean, cryosphere and sea level. Chapter 5 addresses the assessment of the global biogeochemical budgets for carbon dioxide, methane, and nitrous

¹ Global warming of 1.5°C: an IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty (SR1.5); Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems (SRCLL); IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC).

oxide and the assessment of carbon and other biogeochemical feedbacks. Chapter 6 assesses changes in the emissions and abundances of individual SLCFs, how these changes affect Earth's energy balance through radiative forcing and feedback in the climate system, the implications of changing climate on air quality, and the implications of SLCF mitigation for climate and for air quality. Chapter 7 addresses Earth's energy budget through advances in observations, understanding and quantification of effective radiative forcing, and the assessment of feedbacks and climate sensitivity. Chapter 8 assesses observed and projected changes in the global water cycle, the physical understanding of the complexity of its response to multiple drivers, and implications for water availability. The physical processes underlying global and regional changes in the ocean, cryosphere and sea level and the understanding of observed and projected future changes since the AR5 and Special Report on the Ocean and Cryosphere in a Changing Climate are assessed in Chapter 9.

The final four chapters of the Report (Chapters 10–12 and the Atlas) are dedicated to the assessment and distillation of regional climate information from multiple lines of evidence at sub-continental to local scales (including urban climate), building on information from previous chapters on large-scale climate and process understanding, with a focus on recent and projected regional changes in mean climate, extremes, and climatic impact-drivers. Chapter 10 assesses the foundations of how regional climate information is distilled from multiple lines of evidence and the interplay between anthropogenic causes and internal variability at regional scales. Chapter 11 addresses changes in weather and climate extremes on global and regional scales, including observed changes and their attribution, as well as projected changes. Chapter 12 assesses the climatic conditions that may lead to impacts and risks across the world's regions. Changes in mean climate at regional scales, in particular observed trends and their attribution and projected future changes in temperature and precipitation, are assessed in the Atlas chapter.

The Interactive Atlas allows flexible spatial and temporal analyses of climate variables, extreme indices and climatic impact-drivers, including datasets underpinning assessment findings across report chapters and syntheses of regional changes.

Specific regional case studies are considered in different chapters, including rainfall changes in the Sahel and Western Africa, South-Western North America, and South-Eastern South America; climate information relevant for water resources in small islands, for Cape Town drought, for the Indian summer monsoon, for Mediterranean summer warming, and for the Hindu Kush Himalaya region; urban climate processes and trends; and the influence of the Arctic on mid-latitude climate.

All chapters contain Frequently Asked Questions, which are grounded in the assessment and written in language that is more accessible to a broad readership and can serve as a resource for teaching and outreach.

Each chapter is accompanied by Supplementary Material, which is available online and provides traceability and transparency for

technical aspects of the assessment, such as descriptions of datasets, models or methodologies supporting chapter analyses.

The Process

This WGI Assessment Report represents the combined efforts of hundreds of leading experts in the field of climate science and has been prepared in accordance with principles and procedures of the IPCC.

A scoping meeting for the Sixth Assessment Report was held in May 2017, and the outlines for the contributions of the three Working Groups were approved at the 46th Session of the Panel in September 2017. Governments and IPCC observer organizations nominated experts for the author team. The team of 198 Coordinating Lead Authors and Lead Authors plus 36 Review Editors selected by the WGI Bureau was accepted at the 55th Session of the IPCC Bureau in January 2018. During the report preparation, a few changes have taken place to address core expertise gaps and to replace authors who were not available anymore. In addition, 615 Contributing Authors provided information to the author teams at their request.

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. A total of 78,007 written review comments were submitted by 1891 individual expert reviewers and 47 governments. The Review Editors for each chapter monitored the review process to ensure that all review comments received appropriate consideration. All review comments and responses are available online on the report website.

Three in-person Lead Author Meetings took place to enhance progress and coordination in the assessment process. These were particularly critical for the intense cross-chapter coordination implied by the new report outline.

We strived to foster an inclusive environment that achieves a rigorous and transparent assessment process. These efforts included greater attention to addressing implicit biases and technical considerations to enhance the participation in the process and increasing the accessibility of the assessed information.

For the first time in the IPCC, WGI recommended the implementation of FAIR (findable, accessible, interoperable, reusable) data principles in the assessment to document and curate the data assessed and included in report figures. The motivation was to increase transparency and accessibility of the assessment, support implementation of the IPCC Error Protocol, and provide for the long-term curation of the assessed digital information. This process was supported by our close collaboration with the IPCC Task Group on Data Support for Climate Change Assessments (TG-Data) established in March 2018.

The COVID-19 pandemic was declared by the World Health Organization at the start the Second Order Draft review. Following an extensive consultation process with IPCC member countries, authors and the scientific community, including editors of relevant

science journals, the timeline of the report was extended by four months to balance the delays and challenges faced by authors and the scientific community with maintaining momentum and timeliness in the assessment process. The review process is critical for the rigor, objectivity and comprehensiveness of the assessment. The adjustments to the timeline facilitated broad participation from scientists and governments in the review process. Stringent scientific rigor and quality of the assessment were maintained despite the pandemic.

The fourth Lead Author Meeting, due to be held in June 2020, was replaced by extensive virtual activities to address the Second Order Draft review comments and topics that cut across multiple chapters. A final virtual Lead Author Meeting was held in February 2021 to finalize the report. Drafting meetings for the Summary for Policymakers also took place through virtual meetings.

Addressing the implications of the COVID-19 pandemic on the assessment process required innovation to facilitate international virtual collaboration, including extra support and training for participants and facilitators, support for participants with internet connectivity challenges, additional advance preparation, shorter and more focused meetings with clear agendas and objectives and duplicated to account for time zones of participants, high levels of transparency – including the provision of written summaries of meetings and decisions, and allotting time for asynchronous contributions to the discussion and decision-making process.

Documenting and understanding barriers to participation due to an increased reliance on online activities and the use of inclusive practices required priority attention in these novel conditions. We gained experience in applying methods to facilitate participatory and inclusive processes in the assessment and recognized the necessity of fostering these approaches over the course of the assessment process, both during and in-between meetings, to build a stronger community of practice within this unique international context. This will be an important legacy for future assessment cycles.

The preparation of the WGI AR6 report was also informed by recommendations from several IPCC expert meetings. The first meeting focused on assessing climate information for regions (in 2018, co-organized by WGI and WGII, and hosted at ICTP, Trieste, Italy), which provided a scoping of the Interactive Atlas. A second meeting focused on short-lived climate forcers (in 2018, co-organized by TFI and WGI, and hosted by the World Meteorological Organization in Geneva, Switzerland), which identified science advances in the understanding of emissions and climate effects of SLCFs and needs for improvements in emission inventories and methodologies. A third meeting on mitigation, sustainability, and climate stabilization scenarios (in 2019, organized by WGIII in Addis Ababa, Ethiopia), led to cross-WG coordination related to scenarios. Recommendations for clarity and readability from the 2016 IPCC Expert Meeting on Communication (organized by the IPCC Secretariat in Oslo, Norway) were taken into account in developing technical guidance, training and resources provided to authors and in particular for the preparation of the text and figures of the Frequently Asked Questions and the Summary for Policymakers.

The Summary for Policymakers was approved line-by-line during the first-ever virtual IPCC approval session, the 14th Session of IPCC Working Group I from 26 July – 06 August 2021, and the underlying Report was accepted during the 54th Session of the IPCC on the 6th August 2021.

Acknowledgements

We are very grateful for the exceptional rigor and dedication of the volunteer Coordinating Lead Authors and Lead Authors throughout this process, who delivered the most comprehensive assessment ever of our physical understanding of climate change. We thank the Review Editors for working alongside the author teams to ensure that the chapters are fully reflective of the input provided through the review process. We express our sincere appreciation to all the government and expert reviewers, including several group reviews from early-career scientists. We thank the many Contributing Authors who provided input and important support to the authors.

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We thank the Vice Chairs of the WGI Bureau for their dedication, guidance and wisdom throughout the preparation of the Report and their support for cross-Working Group coordination: Edwin Aldrian, Fatima Driouech, Gregory Flato, Jan Fuglestedt, Muhammad I. Tariq, Carolina Vera and Noureddine Yassaa.

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The approval of the WGI Summary for Policymakers took place in an unprecedented context, with travel restrictions caused by the COVID-19 pandemic rendering an in-person IPCC Plenary session impossible. We thank the support and advice of the IPCC Executive Committee and the tireless work of the ad-hoc task group that was established to advise us as Co-Chairs in preparing for the approval session. The task group was led by IPCC Vice-Chair Ko Barrett and included WGI Vice-Chairs Fatima Driouech, Greg Flato and Edwin Aldrian; Anna Pirani and Sarah Connors of the WGI TSU; and Ermira Fida of the IPCC Secretariat. The task group prepared guidance for participants on the modalities of the session and a carefully structured meeting schedule to implement a virtual approval process.

The approval took place virtually for the first time and involved more than 186 hours of online meetings. We thank all participants for the remarkable collaborative spirit and rigorous work undertaken during the session. IPCC Vice Chairs Ko Barrett, Thelma Krug and Youba Sokona brought their unwavering support to facilitate discussions amongst authors and delegations and provided core support for the success of the approval process. We are also grateful to the Vice Chairs of WGI, as well as Mark Howden and Andy Reisinger, Vice Chairs of WGII and WGIII respectively, and Jim Skea, Co-Chair of WGIII, for their support to facilitate the discussions. The WGI TSU was joined by members of the WGII and WGIII TSUs, as well as past interns and chapter scientists to staff this Herculean coordination effort.

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A core outcome of the report has been the development of the WGI Interactive Atlas produced by the Atlas chapter team. The Atlas is dedicated to the memory of Gemma Teresa Narisma, who co-led this innovative chapter with her extensive experience in regional climate research and outstanding leadership. The development and technical implementation have been supported with in-kind contribution from the Spanish government through the Spanish Research Council (CSIC) Instituto de Física de Cantabria, in partnership with Predictia Intelligent Data Solutions. Funding from the Spanish Research & Development program is acknowledged (ref. PID2019-111481RB-I00). We thank the modelling centres and institutions that produce and make available the datasets used in this work. The Interactive Atlas was first made available along with the rest of the Report on 9 August 2021 and was visited by more than half a million users worldwide during the first month.

The WGI TSU has initiated the process to archive the data and code from the report, building on the guidance and support from a large group of contributors. We are indebted to the members of the IPCC Task Group on Data Support for Climate Change Assessments (TG-Data) for their oversight, expert guidance and constant encouragement, including the Co-chairs of the Task Group, David Huard and Sebastian Vicuna, and members representing the WGI science community, Michio Kawamiya, Silvina Solman, José Manuel Guttierrez and Nana Ama Browne Klutse. For the preparation of the figure data and code for archival, we especially thank to our dedicated contractor, Lina Sitz.

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A special thanks goes to the visual design team of the Summary for Policymakers: Tom Johansen and Angela Morelli of Information Design Lab and Jordan Harold and Irene Lorenzoni of the Tyndall Centre for Climate Change Research, as well as to Nigel Hawtin for graphical design support of the Report. We would like to thank Alisa Singer for creating the “Changing” artwork inspired by one of the scientific figures for the front cover of the Report.

Our particular appreciation goes to the WGI TSU, whose tireless dedication, professionalism and enthusiasm underpinned the production of this Report. The Report could not have been prepared without the commitment of members of the TSU, all new to the IPCC, who rose to the unprecedented Sixth Assessment Report challenge and were pivotal in all aspects of the preparation of the Report: Anna Pirani, Clotilde Péan, Sarah Connors, Yang Chen, Robin Matthews, Melissa Gomis, Sophie Berger, Leah Goldfarb, Rong Yu, Baiquan Zhou, Ozge Yelekci, Nada Caud, Katherine Leitzell, Tom Maycock, Mengtian Huang, Elisabeth Lonnoy, Tim Waterfield and Diego Cammarano.

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We wish to express our sincere recognition to all those who contributed to the WGI assessment given the implications of undertaking this during the COVID-19 pandemic, all of whom have worked from home under such challenging conditions.

Finally, on behalf of all the participants to this unprecedented experience, we would like to thank colleagues, friends, and families who have also been part of this intense journey for their understanding and support.

This report shows that how much climate change we experience in the future depends on our decisions now, and what to prepare for. We wish that this report is widely used to provide evidence-based knowledge to inform decision-making, for teaching and training, and to enhance climate literacy worldwide.



Valérie Masson-Delmotte
IPCC Working Group I Co-Chair

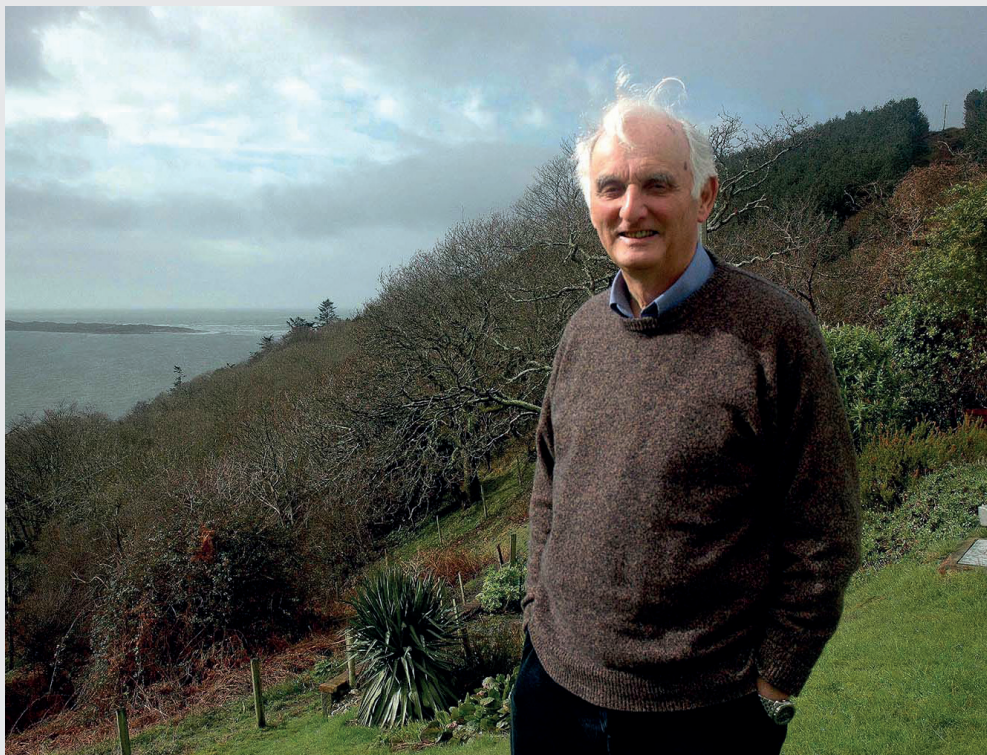


Panmao Zhai
IPCC Working Group I Co-Chair

Dedication

Sir John Houghton

(30 December 1931 – 15 April 2020)



The Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) *Climate Change 2021: The Physical Science Basis* is dedicated to the memory of Sir John Houghton, who was one of the key figures in the creation of the IPCC in 1988, and served as Chair and Co-Chair of Working Group I for the IPCC's first three assessment reports from 1988 to 2002.

Sir John's work was a major factor in the award of the Nobel Peace Prize to the IPCC in 2007, shared with former U.S. Vice-President Al Gore. He contributed to the development of climate science and building international cooperation based upon climate research. Sir John played a key role in ensuring a robust science-policy interface, used in the IPCC process, but his role in international scientific research extended beyond the IPCC, for instance in contributing to the establishment of the World Climate Research Programme, which he chaired from 1982 to 1984.

Sir John was a brilliant communicator among scientific colleagues, policymakers and the public at large, explaining the fact and threat of climate change with clarity and directness.

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