



Guide to the Science of Climate Change in the 21st Century

Chapter 1 Introduction

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1. Introduction

1.1 Overview of Guide

Everything on Earth has a close relationship with climate including humans. It is interesting to reflect on what the human relationship with climate has been and how it has evolved. Again, the human relationship with climate is the most important factor in the evolutionary process. (Thorough discussions of this hypothesis may be found in this excerpt from the Smithsonian Natural History Museum human evolution research program, <https://humanorigins.si.edu/research/climate-and-human-evolution/climate-effects-human-evolution> and <https://www.climate.gov/news-features/climate-and/climate-and-human-evolution> and The National Academy of Sciences publication, Understanding Climate's Influence on Human Evolution, , <https://www.ncbi.nlm.nih.gov/books/NBK208106/>). A term, the anthropogenic era, has been created to identify this time.

Humans' activities are causing climate changes which appear to be determining the biologic future of Earth. It is possible to make these attributions because of the knowledge gained as a result of the study of the science of climate change. It is possible to forecast the implications of future human activities on climate, the environment and nature, and develop strategies to avoid the most undesirable outcomes. Failure to respond in a timely fashion will result in the next great extinction of life the Earth, the Holocene or sixth extinction. This is a legacy the current generation does not want.

A guest post in the newsletter Carbon Brief 11.10.21, <https://www.carbonbrief.org/guest-post-what-100000-studies-tell-us-about-climate-impacts-around-the-world>, concludes after reviewing 100,000 studies: "Our findings show that the influence of human-caused warmings on average temperature and rainfall can already be felt for 85% of the world's population and 80% of the world's area."

The science of climate change is accepted by the scientific community. In Environmental Research Letters published 19 October 2021, https://iopscience.iop.org/article/10.1088/1748-9326/ac2966?utm_campaign=Carbon%20Brief%20Daily%20Briefing&utm_content=20211020&utm_medium=email&utm_source=Revue%20Daily, it was stated that there is "greater than 99% consensus on human caused climate change in peer-reviewed scientific literature".

This Guide follows directly from a short course on the science of global warming and climate change given through the University of Calgary, Canada, over the past twelve years. There were several other presentations on the subject given to consulting engineering groups, public school groups and faith-based organizations. The students and audiences have been very diverse with

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respect to education, age (twelve to eighty years), profession, work experience and life experience. To the knowledge of the author the course and presentations were well received.

There are many sources which describe the science of climate change. Most have their origins in the various publications of the United Nations Intergovernmental Panel on Climate Change (UN IPCC) or sources that have contributed to them. The IPCC was created to provide policymakers with regular scientific assessments on climate change, its implications and potential future risks as well as to put forward adaptation and mitigation options. The IPCC was created by the United Nations Environment Program (UNEP) and the World Meteorological Organization (WMO) in 1988 and has 195 members. The IPCC does not conduct its own research. IPCC reports are neutral, policy-relevant, but not policy-prescriptive. In 2007 the Intergovernmental Panel on Climate Change and Albert Arnold (Al) Gore Jr. were awarded the Nobel Peace Prize “for their efforts to build up and disseminate greater knowledge about man-made climate change, and to lay the foundations for the measures that are needed to counteract such change.”

The IPCC has produced six assessment reports since 1990. Each assessment report has three components; first, the physical science basis, second, impacts, adaptation and vulnerability and third, mitigation of climate change. The working groups, composed of reputable scientists, for each of the reports are referred to as WG1, WG2, and WG3 respectively. Web sites for each of the full reports and the physical science basis are provided. There are a variety of supplementary reports which provide synthesis, policy maker summaries and supplements. Other reports and conference proceedings are available which support the full reports and are very important for the background information they provide. The various IPCC publications provide information to the United Nations Framework Convention on Climate Change (UNFCCC) that was formed in 1992. Periodically, the UNFCCC holds meetings, known as ‘conference of the parties’ (COP) referring to the membership in the UNFCCC in which they develop global strategies to aid in adaptation and mitigation of the recommendations of the IPCC.

Three IPCC Special Reports were published in 2019 with the hope of pre-strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty prior to Conference of the Parties 26, COP26, held in Glasgow, Scotland 31 October – 12 November, 2021. IPCC has published the Assessment Report AR6 WG1 Climate Change 2021: The Physical Science Basis on August 9, 2021, Assessment Report AR6 WG2 Climate Change 2021: Impacts, Adaptation and Vulnerability, February 28, 2022 and Assessment Report AR6 WG3 Climate Change 2021: Mitigation of Climate Change April 4, 2022.

A complete list of reports from the different working groups of the IPCC Sixth Assessment Report, AR6, <https://www.ipcc.ch/assessment-report/ar6/> are as follows:

- AR6 WGI Climate Change 2021: The Physical Science Basis was published August 9, 2021 <https://www.ipcc.ch/report/ar6/wg1/#FullReport>.

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- AR6 WGII Climate Change 2022: Impacts, Adaptation and Vulnerability was published February 28, 2022 <https://www.ipcc.ch/report/sixth-assessment-report-working-group-ii/>.
- AR6 WGIII Climate Change 2022: Mitigation of Climate Change was published April 4, 2022 https://report.ipcc.ch/ar6wg3/pdf/IPCC_AR6_WGIII_FinalDraft_FullReport.pdf.
- AR6 Synthesis Report: Climate Change 2023 was published in March 2023, <https://www.ipcc.ch/report/sixth-assessment-report-cycle/> .

Three other reports that have been published since AR5 and considered to be part of the AR6 cycle are:

- Special Report Global Warming of 1.5°C was approved by the IPCC on October 8, 2018 <https://www.ipcc.ch/sr15/>.
- Special Report Climate Change and Land was published August 8, 2019 <https://www.ipcc.ch/srccl/>.
- Special Report Ocean and the Cryosphere was published September 24, 2019, <https://www.ipcc.ch/srocc/>.

The IPCC also published 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories was published May 2019 <https://www.ipcc.ch/report/2019-refinement-to-the-2006-ipcc-guidelines-for-national-greenhouse-gas-inventories/> .

Another report that is currently in preparation is ‘Methodology Report on Short-lived Climate Forcers’ <https://www.ipcc.ch/report/methodology-report-on-short-lived-climate-forcers/> .

On December 12, 2015, COP21 in Paris, reached ‘a landmark agreement to combat climate change and to accelerate and intensify actions and investments needed for a sustainable low carbon future’. This is known as the ‘Paris Agreement’. Its objective is ‘to pursue efforts to limit the (global) temperature rise this century well below 2 degrees Celsius above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 degrees Celsius. Additionally, the agreement aims to increase the ability of countries to deal with the impacts of climate change, and at making finance flows consistent with a low GHG emissions and climate-resilient pathway’. (<https://unfccc.int/process-and-meetings/the-paris-agreement/what-is-the-paris-agreement>) Several conventions have followed with the purpose to make the Paris Agreement fully operational. COP26 took place in Glasgow, Scotland on November 1 to 12, 2021 (<https://www.ukcop26.org/>) COP27 took place in Egypt November 6 to 20, 2022 (<https://unfccc.int/cop27>).

For reasons of accuracy and completeness the IPCC publications are substantial documents. For most people these reports are a challenge to read and understand even in a synopsis form. If its any comfort there are few if any scientists who can say they understand all of the subjects

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included in the science. But scientists believe scientists.

The purpose of this Guide is to provide a comprehensive introduction to the science of climate change. The material is presented requires little or no previous education or knowledge on any of the subjects beyond junior high school. Terminology is introduced that can be further searched on the internet or elsewhere as desired or required.

The Chapters of the Guide can be read one at a time, in any order – more-or-less. It is not necessary to start at Chapter 1 and continuing to the end. The Chapters do flow one to the next, but some of the them might be difficult reading. For example, one may wish to read about climate models or observations of climate change which is perfectly reasonable and possible without reading other chapters.

The Guide is separated into twenty-four chapters. The sequence is consistent with the IPCC approach. Content for Chapters 2 to 15 are taken from a wide variety of sources including some from the IPCC reports. From Chapter 16 to 21 IPCC content dominates because of their role in the development and application of climate models, predictions and discussions on adaptation and mitigation.

Chapter 2 provides an overview of the history of the scientific study of climate change. It is important to know that the science was discovered at a time when Darwin and the theories on evolution were being developed. It is not a recent construct to serve other interests.

Chapter 3 clarifies the differences between weather and climate.

Chapter 4 is perhaps one of the most important and difficult for scholars of climate to understand. The global energy budget forms the framework for all further discussion on global warming and climate change. It is worth the effort to thoroughly understand the energy budget as it is the basis for the science.

Chapter 5 discusses the carbon cycle which is essential when considering the storage, movement, origins, fate and opportunities for management of the most important greenhouse gas, carbon dioxide.

Chapter 6 discusses the hydrological cycle, water occurrence, movement and storage.

Chapter 7 outlines present basic understanding of the very complex global circulation of the atmosphere, the development of weather and movement of energy around the globe.

Chapter 8 outlines present basic knowledge of circulation of water in the ocean. It provides

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some idea of how energy moves throughout the globe and how it will inevitably affect climate and ocean habitat.

Chapter 9 discusses regional climate variations known as seasons around which all life on Earth has adjusted to, and how changes in climate might affect their occurrence and characteristics.

Chapter 10 discusses a significant weather phenomenon collectively known as cyclones which are significant because of their destructive potential. It is important to understand the factors that determine their occurrence and strength and how these might be connected to climate change.

Chapter 11 discusses the El Niño-Southern Oscillation (ENSO), an important atmosphere-ocean system, which occurs in the south Pacific but affects weather systems around the world through a process known as teleconnection. Several other atmosphere-ocean systems have been identified and known to have significant short and long effects on regional weather and ocean characteristics. ENSO is the most dramatic.

Chapter 12 identifies and discusses the natural forces which cause climate change that is evident in studies of paleoclimatology, the subject of Chapter 13. The fact that climate change has occurred since Earth was formed is evident in the geology. The study of paleoclimatology helps identify when the various changes occurred and what they were. There is considerable, reliable, and detailed knowledge on how Earth's climate has changed over the past 800,000 years. Palaeoclimatological studies allow characterization of Earth's climate before actual measurements were being made.

Chapter 14, the modern instrumental period, discusses how methodology for observing weather has evolved since the beginning of the use instruments to measure temperature and precipitation and how the observation of most of the elements in the energy budget, on a global scale, is achieved using satellite technology and advanced data management techniques only possible with advances in computer technology.

Chapter 15 discusses greenhouse gases, what they are and how they are quantified and introduces how they are measured locally and on a global scale.

Chapter 16 describes observed impacts of recent climate change, the motivating force behind the development of climate science and climate models which is discussed in Chapter 17. The development of climate models was necessary to consider all of the factors that affect climate, worldwide. The capability, validity and use of the numerous climate models are discussed.

Chapter 18 discusses how the projected impacts of climate change on physical systems were

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arrived at, including the scenarios, known as representative concentration pathways (RCPs), were used.

Chapter 19 provides an overview of how the projected physical impacts are used to identify impacts on nature (biological systems) and on humans and human managed systems and how opportunities for adaptation may be identified.

Chapter 20 introduces climate change mitigation and the various strategies available to perform mitigation.

Chapter 21 introduces the Sixth Assessment Report, AR6 WGI Climate Change 2021: The Physical Science Basis published August 9, 2021.

Chapter 22 introduces the Sixth Assessment Report, AR6 WGII Climate Change 2022: Impacts, Adaptation and Vulnerability

Chapter 23 introduces the Sixth Assessment Report, AR6 WGIII Climate Change 2022: Mitigation

Chapter 24 Introduces the Sixth Assessment Report, Synthesis Report, a summary of AR6 WGI, WGII and WGIII.

Chapter 25 Closure and personal opinion regarding the science of climate change climate change management.

Chapter 26 Discussion Presentation #11, Climate Change Canada and Alberta, a review of how the various levels of government are communicating climate change issues and what actions they are taking to deal with climate change education, communication, adaptation and mitigation.

Chapter 27 Discussion Presentation #12, Climate Change Denial, a review of denial issues.

Chapter 28 Glossary, refers to glossaries published by IPCC and others.

Chapter 29 Selected web sites that provide supportive information. Web sites from several educational organization, useful newsletters and international organizations.

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- Chapter 2.0 History of the Scientific Study of Climate Change
- Chapter 3.0 Weather and Climate
- Chapter 4.0 Earth’s Energy Budget
- Chapter 5.0 Carbon Cycle
- Chapter 6.0 Hydrological Cycle
- Chapter 7.0 Global Circulation of the Atmosphere
- Chapter 8.0 Global Circulation of Water in the Ocean
- Chapter 9.0 Climate and Seasons
- Chapter 10.0 Hurricanes, Typhoons and Cyclones
- Chapter 11.0 El Niño-Southern Oscillation (El Niño and La Niña)
- Chapter 12.0 Climate Change – Natural Forces
- Chapter 13.0 Paleoclimatology
- Chapter 14.0 Modern Instrumental Period
- Chapter 15.0 Greenhouse Gas
- Chapter 16.0 Observation and Impacts of Recent Climate Change
- Chapter 17.0 Climate Models
- Chapter 18.0 AR5 - Impacts of Climate Change on Physical Systems
- Chapter 19.0 AR5 - Adaptation
- Chapter 20.0 AR5 - Mitigation
- Chapter 21.0 Sixth Assessment Report, August 9, 2021 – AR6 WGI Climate Change 2021: The Physical Science Basis
- Chapter 22.0 Sixth Assessment Report, February 28, 2022 – AR6 WGII Climate Change 2022: Impacts, Adaptation and Vulnerability
- Chapter 23.0 Sixth Assessment Report, April, 2022 – AR6 WGIII Climate Change 2022: Mitigation
- Chapter 24.0 Sixth Assessment Report, Synthesis, March 2023
- Chapter 25.0 Comments
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- Chapter 28.0 Glossary
- Chapter 29.0 Selected Web Sites

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The United Nations Department of Economic and Social Affairs, Sustainable Development lists seventeen sustainable development goals (SDGs) (<https://sdgs.un.org/goals>) listed in Table 1.2. These cannot be successfully addressed without resolving the climate change crisis.

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1. No poverty.
2. Zero hunger.
3. Good health and well-being.
4. Quality education.
5. Gender equality.
6. Clean water and sanitation.
7. Affordable and clean energy.
8. Decent work and economic growth.
9. Industry, innovation and infrastructure.
10. Reduced inequalities.
11. Sustainable cities and communities.
12. Responsible consumption and production.
13. Climate action.
14. Life below water.
15. Life on land.
16. Peace, justice and strong institutions.
17. Partnerships for the goals.

Table 1.2 United Nations ‘Sustainable Development Goals’.

It is hoped that readers will wish to continue their studies on the science of climate change by engaging in further exploration of the concepts presented in this Guide and begin to study the various IPCC reports themselves. To meet this need, a content support section is included at the end of each chapter which provides a limited list of useful web sites, useful books, videos and selected references if available or relevant.

As already mentioned, access to quality information on almost any subject is available in a timely fashion on the internet. There is also questionable and misleading information. The internet has the advantage of being able to provide the most up-to-date knowledge from the best sources – once you know how to identify them. The veracity of information can be cross-checked easily by also accessing other web sites, particularly those supported by reputable organizations. Peer reviewed published articles may also be found – information that would be very difficult to come by any other way. Web sites appear, disappear and change and for this reason only a few web sites that are considered the best available long-term sources are listed.

There are several on-line courses on the science of climate change supported by very reputable universities and government agencies that can provide other perspectives on the topics introduced in this Guide. Several are listed in Chapter 24.

A word of caution about published articles, peer reviewed or otherwise. Simply because the

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research is published does not mean it was or remains ‘fact’. Papers and research reported may be superseded by recent thought and research. New research might make the previously published work irrelevant, obsolete and even prove that previous research was not completely correct. Care must always be taken. The screening process used by the IPCC in the preparation of their reports is particularly useful in this regard. Information in published articles can usually be further explored on the web.

Additional information on all of the subjects covered in this Guide is constantly being published. To the extent possible the Guide is updated regularly. Readers may wish to participate in this process by subscribing to one or more of the newsletters listed in Chapter 24.

Section 1.3 on other important organizations provides some insight as to how much scientists and interested parties network and how these interactions are encouraged and supported. This activity and these organizations keep the global community updated on developments on the science of global warming and climate change. There are many other organizations at the national and international level (learned societies for example) that are also important but are so numerous that it is beyond the scope of this Guide to list.

1.2 Special note on Nobel Prize winners

The 2021 Nobel Prize in Physics was awarded to Syukuro Manabe and Klaus Hasselmann who each shared ¼ of the prize “for the physical modelling of Earth’s climate, quantifying variability and reliability of predicting global warming”. The other half of the prize was awarded to Giorgio Parisi “for the discovery of the interplay of disorder and fluctuations in physical systems from atomic to planetary scales”. See

<https://www.nobelprize.org/prizes/physics/2021/summary/>,
<https://www.nobelprize.org/prizes/physics/> and https://www.nature.com/articles/d41586-021-02703-3?utm_source=Nature+Briefing&utm_campaign=38fd982e90-briefing-dy-20211008&utm_medium=email&utm_term=0_c9dfd39373-38fd982e90-46124954.

The 2007 Nobel Peace Prize was awarded jointly to the IPCC and Al Gore “for their efforts to build up and disseminate greater knowledge about man-made climate change, and to lay the foundations for the measures that are needed to counteract such change”. See

<https://www.nobelprize.org/prizes/peace/2007/summary/> and
<https://www.nobelpeaceprize.org/laureates/2007>.

1.3 International organizations

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There are many organizations, in virtually every country in the world, which reach out to educate and invite participation in developing actionable strategies to solve adaptation and mitigation issues. Individuals have opportunities to contribute to discussions pertaining to their local community to discussions pertaining to the global community.

There are many well trained and knowledgeable individuals in the scientific community, a.k.a. scientists, working independently or part of a group. They might be part of a local, provincial, national or international organization which are operating as part of government programs, university and college programs (graduate and post-graduate), learned societies, independent institutes and more. Most of the research is eventually published in reputable journals after a thorough peer review process.

The two best-known international organizations are the Intergovernmental Panel on Climate Change, IPCC (<https://www.ipcc.ch/>) and the United Nations Framework Convention on Climate Change, UNFCCC (<https://unfccc.int/>). As will be noted in their web sites there is a significant effort to provide networking opportunities to anyone, not just scientists, interested in any aspect of the science of global warming and climate change and adaptation and mitigation. Many researchers from many disciplines participate in the development of the IPCC assessment reports and in the extensive support system required to produce the reports.

A few very important international organizations that network active individual scientists and organizations doing significant research into the various aspects of the science of global warming and climate change are the World Meteorological Association (<https://public.wmo.int/en>), the United Nations Environment Programme, UNEP, (<https://www.unep.org/>), the World Climate Research Program (<https://www.wcrp-climate.org/>) and Future Earth (<https://futureearth.org/>). The web site of each organization is worth exploring.

1.3.1 World Meteorological Organization

The World Meteorological Organization is a specialized agency of the United Nations <https://public.wmo.int/en>. They state their mandate as follows; ‘As weather, climate and the water cycle know no national boundaries, international cooperation at a global scale is essential to implement an Earth system approach for the development of meteorology, climatology, operational hydrology and related environmental services as well as to reap the benefits from application. WMO provides the framework for such international cooperation.’

WMO publishes a report in 2022 titled, United in Science 2022: A multi-organizational high-level compilation of the most recent science related to climate change, impacts and responses. United in Science reports are available for 2019, 2020 and 2021. United in Science reports are an update on the most recent IPCC reports. In their words “United in Science provides an

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overview of the most recent science related to climate change, impacts and responses from the World Meteorological Organization (WMO) and partner organizations. At a time when urgent action to address climate change is needed, the report provides unified scientific information to inform decision-makers and highlights some of the physical and socioeconomic impacts of the current and projected climate.” The reports are available for download at https://library.wmo.int/index.php?lvl=notice_display&id=22128#.Yzx5FXbMIuV .

1.3.2 United Nations Environment Programme, UNEP

The United Nations Environment Programme, UNEP, <https://www.unep.org/> is the implementing arm of the United Nations Environment Assembly <https://www.unep.org/environmentassembly/about-united-nations-environment-assembly> which is described itself as follows; ‘The United Nations Environment Assembly is the world’s highest-level decision-making body on the environment. It addresses the critical environmental challenges facing the world today. Understanding these challenges and preserving and rehabilitating our environment is at the heart of the 2030 Agenda for Sustainable Development.

The Environment Assembly meets biennially to set priorities for global environmental policies and develop international environmental law. Through its resolutions and calls to action, the Assembly provides leadership and catalyses intergovernmental action on the environment. Decision-making requires broad participation, which is why the Assembly provides an opportunity for all peoples to help design solutions for our planet’s health.’

‘UNEP’s mission is to provide leadership and encourage partnership in caring for the environment by inspiring, informing, and enabling nations and peoples to improve their quality of life without compromising that of future generations.’ ‘UNEP works on delivering transformational change for people and nature by drilling down on the root causes of the three planetary crises of climate change, nature and biodiversity loss, and pollution and waste.’

1.3.3 World Climate Research Programme

The World Climate Research Programme (WCRP) <https://www.wcrp-climate.org/> leads the way in addressing frontier scientific questions related to the coupled climate system — questions that are too large and too complex to be tackled by a single nation, agency or scientific discipline. Through international science coordination and partnerships, WCRP contributes to advancing our understanding of the multi-scale dynamic interactions between natural and social systems that affect climate. WCRP engages productively through these partnerships to inform the development of policies and services and to promote science education. Most critically, WCRP-supported research provides the climate science that underpins the United Nations Framework Convention on Climate Change, including national commitments under the Paris Agreement of 2015, and contributes to the knowledge that supports the 2030 Agenda for

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Sustainable Development, the Sendai Framework for Disaster Risk Reduction, and multilateral environmental conventions.

In their own words, ‘The World Climate Research Program coordinates and facilitates international climate research to develop, share, and apply the climate knowledge that contributes to societal well-being. We seek to better understand the climate system. Our research aims to predict the near-term evolution of the climate system. We strive to better understand long-term responses to the climate system. We will build a bridge between climate science and society.’

1.3.4 Future Earth

‘Future Earth <https://futureearth.org/> is a global network of researchers and innovators. The strength of Future Earth lies within the work of the community comprising 27 Global Research Networks (formerly referred to as 8 Knowledge Action Networks and 19 Global Research Projects), and National and Regional Networks (National Committees and Structures, Regional Committees and Offices), as well as the Early Career Network. These networks represent academics, policymakers, independent scholars, and students, all working across sectors and disciplines. They play a critical role in defining and advancing research and solutions in Earth system science and its component sub-systems and their nexus (land, ocean, food, energy, water, etc.), including human societies and health. The secretariat works to connect the networks and drives synthesis and engagement across the different networks, including communications products and links to policy communities at a global level.’ The Global Carbon Project <https://www.globalcarbonproject.org/index.htm> is a Global Research Project of Future Earth and is discussed in Chapter 15.

They elaborate in their 2021 Annual Report (https://futureearth.org/wp-content/uploads/2022/09/future-earth_finalWEB.pdf); ‘Future Earth continues to develop knowledge products for society, such as technical papers submitted to the Convention on Biological Diversity and the delivery of 10 New Insights in Climate Science to the United Nations Framework Convention on Climate Change (UNFCCC) at COP26 in Glasgow. The Earth Commission continued to advance on its assessment of tipping points in the Earth system to define safe and just Earth system boundaries to underpin science-based targets for businesses and cities. Sustainability in the Digital Age also launched a Digital Climate Projects Database focused on climate governance strategies. Each of these products translates the most recent scientific understanding into a user-oriented frame for greater relevance and uptake to communities at the forefront of change.’

1.4 Information support

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Key web sites:

1. Paris Agreement, COP21. <https://unfccc.int/process-and-meetings/the-paris-agreement/what-is-the-paris-agreement>.
2. UNFCC. <https://unfccc.int/>.
3. UN IPCC. <https://www.ipcc.ch/>.
4. IPCC First assessment report science. <https://www.ipcc.ch/report/ar1/wg1/>.
5. IPCC Second assessment report science. <https://www.ipcc.ch/report/ar2/wg1/>.
6. IPCC Third assessment report science. <https://www.ipcc.ch/report/ar3/wg1/>.
7. IPCC Fourth assessment report science. <https://www.ipcc.ch/report/ar4/wg1/>.
8. IPCC Fifth assessment report science. <https://www.ipcc.ch/report/ar5/wg1/>.
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