Kate Meyer
Peter Newman

Planetary Accounting

Quantifying How to Live Within Planetary Limits at Different Scales of Human Activity

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Dedicated to Kate's children Patrick and Hazel and Peter's grandchildren Josie, Lilah and Benji. We hope planetary accounting will help to create a healthier planet for your generation.

Preface

There is a lot of science in this book, but a lot of other stuff too. We both know that science is really important to the issues we are addressing but each of us has lived in other realms of life, where we have learned a lot of “other stuff”. I have a PhD in Chemistry, studied Environmental Science, and in 2018/2019 was named as Western Australian Scientist of the Year. Kate is a Mechanical Engineer and has just completed her PhD. So, we qualify to address the scientific issues, and we spent a lot of time working to make sure we had the science of Planetary Boundaries right. But why we feel this book has something that nobody else has done is that we have integrated the science of how the world is changing with how you change the world to make it better.

The scientists who produced the Planetary Boundary publications did a remarkable job. They had to bring so much together from so many varied scientific journals and make it into a sensible set of conclusions—very scary conclusions about the state of the planet. However, there has been a reasonable time that has passed since these publications and they were communicated very strongly in science media outlets, but it has not made much impression on the general public, businesses, or politicians. While some governments and businesses see the value in applying the Planetary Boundaries, this has taken considerable effort for each organization and the outcomes are typically incomplete and ad hoc. We think we know why and have written a book to enable us to see if our approach helps make it more possible to have a coherent approach about making our world better on all the Planetary Boundaries.

The reason we believe it has not been well understood beyond the first reaction of “this is terrible” is that the Planetary Boundaries are not in metrics that are comparable with human activity and decision-making. They are not even the same type of metrics; they are apples and oranges which cannot be compared. They also cannot be scaled into meaningful parameters where we can take responsibility at different levels. So, we have tried to fix this.

The reason we were able to see the issues and had an approach to fix it is because we have both worked with industry and with governments on policy-oriented environmental tools. These tools come from State of the Environment Reporting which has been set up at all levels of government and industry, and we also have been closely involved in local community groups and local governments where people are trying to work out what environmental responsibility means for them.

So, we have brought a different perspective to the Planetary Boundaries that is based on a number of other areas of expertise in the social sciences and humanities.

The other motivation behind this book is that we are parents and even grandparents in my case. You cannot look into the eyes of your own progeny without worrying about whether we have some hope for their future. This book is aimed at providing that hope.

If you do not think we are serious, then you should know that in order to get the science of Planetary Boundaries right, and to see if the scientists who did this amazing compilation of science can agree with the approaches we have taken to reframe them, Kate had to go and meet them all, mostly in Europe. She packed up her husband and two young children, bought a van and drove around Europe for 8 months, presenting seminars and having in-depth discussions with the scientists. She even had the van towed away at night once, leaving her and her family stranded with nowhere to sleep! This is real commitment. Check out Kate's blog if you want to know more https://airphd.wordpress.com/.

We are keen therefore that you read this and see what you can do about the suggested solutions. We need lots of suggestions for what can be done with the new tools we have created. And we are happy to recognize you in any further publications we do on the subject. So write to us, we are not hard to find at Curtin University or the Planetary Accounting Network https://www.planetaryaccounting.org/.

Western Australia, WA, Australia Peter Newman

Contents

Chapter 1
Introduction

Abstract Nine Planetary Boundaries were determined by a group of Earth-system scientists in 2009 but little social and political change towards address them has happened. Our book shows why and how this can be fixed through creating Planetary Accounting based on three social science theories. This introductory chapter provides an overview of how this will be done.

1.1 The Journey

Our planet is changing. One-in-one-hundred-year storms are becoming the norm. News articles about imminent species extinctions no longer feel shocking. They are expected. Images of oceans full of plastic litter social media. An island near Hawaii has been taken off the map as it has been engulfed by rising sea levels. The chemical composition of our atmosphere has not previously been experienced by humankind.

In 2009, 28 internationally renowned Earth-system scientists led by Johan Rockström at the Stockholm Resilience Centre (Rockström et al. 2009) identified nine Planetary Boundaries (PBs)—critical global environmental limits within which the risk of fundamentally changing the state of the planet is low: a "safe operating space" for humankind. If human activity pushes the planet beyond these limits, we are at risk of changing the state of the planet. The alternative state, beyond these limits, is uncertain, but it is likely to be hotter, less stable, and less favourable to humankind. Four of the PBs have been transgressed, the PBs for climate change, biogeochemical flows, land use, and biodiversity loss (Steffen et al. 2015). The situation is urgent. The risk that human activity will irrevocably change the state of the planet is high. We ought to manage human activity such that we can live well within the safe operating space. The problem is how?

In the face of this global environmental crisis, it can be hard to imagine what you could do to help. The PBs convey important information about the health of the planet. However, they do not tell us what to do. They are limits for the environment, not for people. They cannot be easily related to human activities. Nor do they make sense at smaller scales. Scientists and policy-makers want to translate the PBs into policy, to use them as the basis for managing human impacts on the

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environment. But the PBs were not designed to be used in this way. They were intended as Earth-system science indicators of the extent and urgency of the problem. They were not meant to be a guide to resolving it. Regional and national environmental targets have been developed using the PBs as guidance, and scientists have established frameworks to try and link the PBs to environmental accounting systems. However, each of these works has limitations, both in their connectivity to the PBs and in their applicability to environmental management. The PBs just do not relate simply to human activity or to different levels of government.

Herein lies the basis of this book. We (the authors) have developed a framework that sets out how to break up global environmental problems into more manageable chunks that you—as an individual, a chief executive, a city councillor, or a national committee member—can tackle. We call it "Planetary Accounting" because it is about creating a series of budgets that can be used to help us manage the global environment from whatever scale of influence we hold. Planetary Accounting can be used to quantify what we all need to do in order to return to and live within the safe operating space of the Planetary Boundaries.

There were three key discoveries that led to the eventual solution of Planetary Accounting (which will be described in much greater detail in the book). The first discovery came from management theory. Current environmental management practices are often through top-down governance or private management. These practices are based on out-of-date theories of environmental management such as the tragedy of the commons—the concept that, in the absence of enforced rules, humans are unable to share resources (such as forests or fisheries) without overusing and exploiting them. More recent findings in the fields of behaviour change, commons management, and change theory can be used to show that a more effective approach would be one that applies at different scales and in different ways—from individual bottom-up initiatives, to business and private sector efforts, to traditional top-down governance. Importantly, these approaches should be coordinated by a general system of rules that has the flexibility to accommodate these different centres of activity. We call this a "poly-scalar approach".

The second key discovery was a critical insight from accounting theory that only if there are standards or limits can you create serious change; that "you cannot manage what you do not measure". Humans have become very good at estimating past, present, and even future environmental impacts from human activity. The ongoing measurement and monitoring of environmental assets (e.g. forests, land, or fisheries) and of our impacts on these is called environmental accounting. It is now common for businesses, cities, and nations to keep environmental accounts—i.e. to track environmental impacts and the state of environmental assets over time against targets and benchmarks. Environmental accounting is an important tool for helping humans to reduce our impacts on the planet as it can be used to inform decision-making at any scale of activity. However, the key limitation is that for most environmental impacts, there is no clearly determined limit. Targets for managing impacts are typically set based on percentage reductions from the status quo or on industry best practice. Such targets are arbitrary. Even where targets are based on local policy or legislation, these are not often based on scientific limits. Moreover, targets that focus on the (negative) status quo can seem exhausting. They convey a sense that people will always need to reduce, reduce, reduce. Rather than generating change, such targets can lead to a feeling of helplessness and despair in the face of our seemingly insurmountable environmental problems. There is a need to connect concrete, science-based targets with existing environmental accounting practices.

The third, and perhaps the most important, discovery that informed this research came from theories about environmental indicators, that different types of environmental indicators serve different purposes. The European Environment Agency developed a framework to categorize environmental indicators, the Driver, Pressure, State, Impact, Response (DPSIR) framework (EEA 2005). Any environmental indicator can be classified as either a Driving force (a human need, such as the need for fuel), a Pressure (a flow to the environment, such as CO_2 emissions), a State (describing the state of the environment, such as the concentration of CO_2 in the atmosphere), an Impact (describing a change in State, such as global warming), or a Response (describing a human response to the environment, e.g. the Paris Agreement).

Human activity directly influences Drivers and Pressures, but only indirectly influences States and Impacts. Both types of indicators are important, but they serve different purposes. State and Impact indicators communicate the status quo. Pressure and Driver indicators communicate action. Confusingly, the PB indicators are not all in the same DPSIR category. Three of the PB indicators are Pressures, five are States, and one is an Impact. The PBs given in State and Impact indicators give an overview of planetary health. They communicate information such as that the concentration of CO_2 in the atmosphere and the rate of species extinctions are too high. This is an important message, but does not quantify what needs to be done. In contrast, the PBs given in Pressure indicators are limits for human activity. They do communicate what we should do, for example, how much freshwater we can safely consume or how much nitrogen we can fixate without pushing the global environment to a point of irreversible change.

The insight that the PB indicators are of varying DPSIR categories is not new. There have been several projects in which the DPSIR framework was used to make the PBs relevant to policy. The first attempt to translate the PBs into policy was the development of national targets for Sweden (Nykvist et al. 2013). The authors identified the need to translate the PBs into Pressure indicators. However, they only achieved this for one of the PBs, the PB for CO_2 concentration. They did not translate the remaining State and Impact PB indicators into limits for Sweden. A later adaptation of the PBs to targets for Switzerland also references the variance in the PB indicator classifications. However, the indicators selected for Switzerland in this study also vary between DPSIR categories. No one has previously translated the full set of PBs into Pressure-based indicators.

The three discoveries described here led us to the conclusion that what was needed was a new type of environmental accounting that incorporated Pressure indicators and science-based targets while retaining enough flexibility to be applied in a ploy-scalar way.

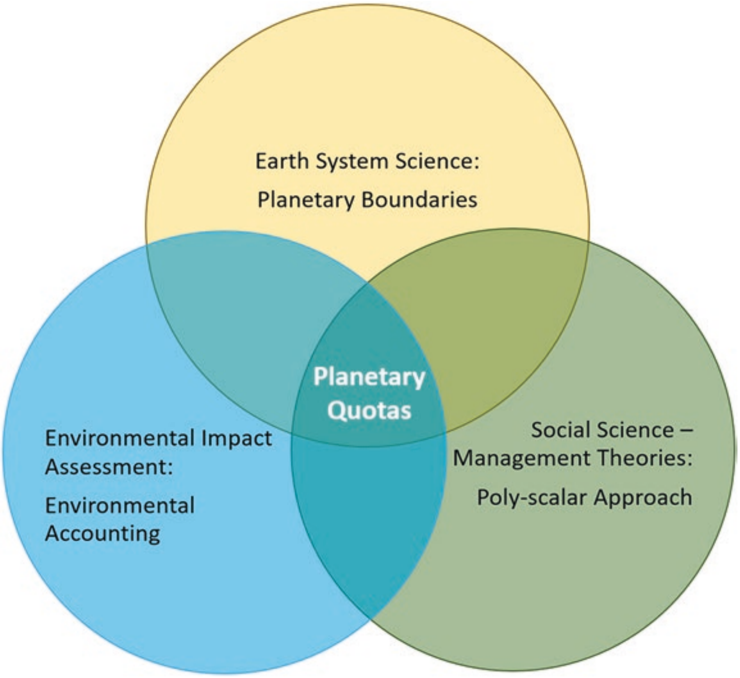

Fig. 1.1 The novel Planetary Quotas bring together the latest advances in Earth-system science (the Planetary Boundaries), environmental impact assessment (environmental accounting), and the social science of management theory (poly-scalar management)

This book thus introduces a new set of global limits, based on the Planetary Boundaries, but using Pressure indicators, the Planetary Quotas (PQs). The PQs bring together the insights from the three fields of research described above by using the DPSIR framework to connect the Planetary Boundaries and environmental accounting in a way that can be used at different scales and for different types of human activity (see Fig. 1.1).

The PQs create the foundation for our new concept—Planetary Accounting—comparing the results of environmental impact assessments to global scientifically determined limits (see Fig. 1.2).

It is our intention that Planetary Accounting will provide a platform for the behaviour, policy, organizational, and technological change that will be needed if we are to return to and live within the safe operating space.

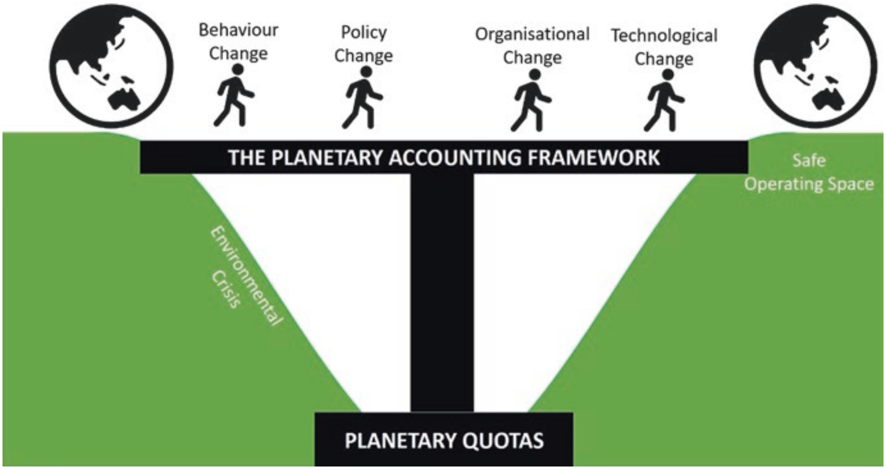

Fig. 1.2 The Planetary Quotas form the foundations of the Planetary Accounting Framework—a platform for change

1.2 A Guide to This Book

This book is divided into three sections. The first provides a review of the literature that led us to the discoveries described in this introduction and goes on to show how these helped us to arrive at the solution of a Planetary Accounting Framework and the Planetary Quotas.

The second section describes the research methods used in the development of the overall concept as well as giving some background to and the scientific basis for each of the Quotas.

The last section of the book summarizes the Planetary Quotas, describes Planetary Accounting and shows how this can be used, and discusses the strengths, limitations, potential applications, and future work in this area.

Section 1

- Chapter 2: The Science of Anthropogenic Climate Change
  This book is based on the assumption that human activity can change and is changing the state of the planet. In recognition that not everyone believes that this assumption is true, this chapter presents the scientific evidence that supports this theory and addresses the key arguments made against it.
- Chapter 3: The Holocene, the Anthropocene, and the Planetary Boundaries
  This chapter provides an overview of past attempts to define the limits for human impacts on the planet. It highlights some of the challenges people have faced in determining global limits and shows why we believe that the Planetary Boundary framework is the most robust and transparent definition for global limits at this point in time and thus forms the basis of Planetary Accounting.
- Chapter 4: Managing the Earth System: Why We Need a Poly-scalar Approach

This chapter summarizes some of the past and present theories of how best to manage shared environmental resources and of how to generate change. It concludes with the case that a poly-scalar approach is needed to manage the Earth system.

- Chapter 5: Environmental Accounting, Absolute Limits, and Systemic Change
  This chapter gives a historical account of environmental impact assessment methods and environmental accounting practices. It shows that a key limitation of most environmental accounting is that the impacts of human activity determined through environmental impact assessments cannot be compared to scientific limits. It demonstrates that absolute, scientific limits are likely to be a key component to achieving systemic change.
- Chapter 6: Resolving the Disconnect Between Earth-System Science, Environmental Management Theory, and Environmental Accounting
  This chapter shows how the DPSIR framework from environmental accounting can be used to show why the Planetary Boundaries are not accessible or applicable to human activity. It concludes that key constraint for using the Planetary Boundaries is that they are not all of a single DPSIR category and that in order to make them accessible, they should be translated into a uniform set of Pressure category indicators.

Section 2

- Chapter 7: Translating the Planetary Boundaries into Planetary Quotas
  This chapter provides a high-level introduction to the Planetary Boundaries and Planetary Quotas. It then describes the overall methodology for the project and the methods used to translate the PBs into PQs.
- Chapter 8: A Planetary Quota for Carbon Dioxide
  This chapter presents the background and need for a Planetary Quota for carbon dioxide and shows the detailed methodology used to derive this.
- Chapter 9: A Planetary Quota for Methane and Nitrous Oxide
  This chapter presents the background and need for a Planetary Quota for methane and nitrous oxide and shows the detailed methodology used to derive this.
- Chapter 10: A Planetary Quota for Forestland
  This chapter presents the background and need for a Planetary Quota for reforestation and shows the detailed methodology used to derive this.
- Chapter 11: A Planetary Quota for Ozone-Depleting Substances
  This chapter presents the background and need for a Planetary Quota for ozone-depleting substances and shows the detailed methodology used to derive this.
- Chapter 12: A Planetary Quota for Aerosols
  This chapter presents the background and need for a Planetary Quota for aerosols and shows the detailed methodology used to derive this.
- Chapter 13: A Planetary Quota for Water
  This chapter presents the background and need for a Planetary Quota for water and shows the detailed methodology used to derive this.
- Chapter 14: A Planetary Quota for Nitrogen

This chapter presents the background and need for a Planetary Quota for nitrogen and shows the detailed methodology used to derive this.

- Chapter 15: A Planetary Quota for Phosphorus
  This chapter presents the background and need for a Planetary Quota for phosphorus and shows the detailed methodology used to derive this.
- Chapter 16: A Planetary Quota for Biodiversity
  This chapter presents the background and need for a Planetary Quota for biodiversity and shows the detailed methodology used to derive this.
- Chapter 17: A Planetary Quota for Imperishable Waste

  This chapter presents the background and need for a Planetary Quota for imperishable waste and shows the detailed methodology used to derive this.

Section 3

- Chapter 18: The Planetary Accounting Framework
  This chapter brings the Planetary Quotas together as a suite of global limits for human activity and shows how these can be used by outlining a high-level Planetary Accounting Framework to inform many different aspects of human activity. It outlines the key strengths and weaknesses of the research project and identifies areas of future work.

1.3 Publications

A summary of this book has been published in the new Springer-Nature-BMD journal *Sustainable Earth:*

Meyer, K. and Newman, P. 2018. Planetary accounting – a quota-based approach to managing the Earth system. *Sustainable Earth* 1:4–25.

The work described in this book was undertaken under the umbrella of a PhD by Kate Meyer and supervised by co-author Peter Newman. The thesis, which provides an extended description of much of the technical information presented in this book, is available from the Curtin University Library (Meyer 2018).

References

EEA (2005) EEA core set of indicators. Guide. Office for Official Publications of the European Communities, Luxembourg

Meyer K (2018) Planetary quotas and the planetary accounting framework - comparing human activity to global environmental limits. PhD, Curtin

Nykvist B, Persson Å, Moberg F, Persson LM, Cornell SE, Rockström J (2013) National environmental performance on planetary boundaries: a study for the Swedish Environmental Protection Agency. Sweden, Swedish Environmental Protection Agency

Rockström J, Steffen W, Noone K, Persson A, Chapin FS, Lambin E, Lenton TM, Scheffer M, Folke C, Schellnhuber HJ, Nykvist B, De Wit CA, Hughes T, Van Der Leeuw S, Rodhe H, Sorlin S, Snyder PK, Costanza R, Svedin U, Falkenmark M, Karlberg L, Corell RW, Fabry VJ, Hansen J, Walker B, Liverman D, Richardson K, Crutzen P, Foley J (2009) Planetary boundaries: exploring the safe operating space for humanity. Ecol Soc 14:32

Steffen W, Richardson K, Rockström J, Cornell SE, Fetzer I, Bennett EM, Biggs R, Carpenter SR, De Vries W, De Wit CA, Folke C, Gerten D, Heinke J, Mace GM, Persson LM, Ramanathan V, Reyers B, Sörlin S (2015) Planetary boundaries: guiding human development on a changing planet. Science 347:1259855

Part I
Earth-System Science, Management Theory, and Environmental Accounting: The Disconnect

Chapter 2
The Science of Anthropogenic Climate Change

We have to wake up to the fierce urgency of the now
Jim Yon Kim

Abstract There is scientific evidence to suggest that human activity, in particular the release of greenhouse gases to the atmosphere, is currently causing the climate to warm up. There is only a 1 in 100,000 chances it is not human activity. A warmer climate is predicted to be unfavourable for humanity. However, there are some people who dispute the theory of anthropogenic climate change, arguing either that the climate is not changing, that the change is not caused by human activity, or that it is not important.

Data taken from multiple sources shows a clear warming trend since preindustrial times. 2016 was the hottest year on record and July, 2019 was the hottest month on record. Average temperatures are now more than 1 °C higher than during preindustrial times.

Greenhouse gases trap shortwave radiation and therefore heat into the atmosphere. Approximately equal quantities of greenhouse gases are emitted and absorbed naturally every year. Human activity releases a relatively small amount of greenhouse gases to the environment compared to natural processes. However, we absorb very little of what we emit. Thus, there is a net flow of these gases to the environment from human activity.

There are no natural factors which correlate with the current warming trends. The primary theory for natural warming is that it is caused by changes in the solar cycle. However, the amount of energy coming from the Sun has been reducing since 1980, and warming has continued.

There have been higher levels of greenhouse gases in the atmosphere before and life has flourished. However, this has been during stable climate conditions. Rapid increases or decreases of greenhouse gases in the past have been highly destructive to life on Earth.

Human-induced climate change is expected to mean less favourable conditions for humankind, as we leave the "zone of comfort" within which cities and agriculture have been able to develop over the past 10,000 years.

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2.1 Introduction

The premise of this book is that human activity is changing the Earth system and that this is one of the greatest risks to humankind. Not all people share this view. The debate between climate change advocates and climate change sceptics in the media is prolific, heated, and emotive. There is name-calling; advocates and sceptics call one another "deniers" and "alarmists". Both sides frequently use the term "myths" to describe the arguments of those opposing their views. Much of the debate in the media has lost any connection with the science at question. Arguments often focus around *who said what* rather than scientific facts. This chapter is therefore setting out to show why Earth-system science is important by applying it to the climate change issue, and also why it is important to understand the human issues behind the controversies.

Despite almost unequivocal scientific evidence to support their case, many advocates continue to fall back on the feeble argument that 97% of climate scientists believe in anthropogenic global warming rather than citing scientific facts to support their case. The views of scientists do not constitute scientific evidence. Further, it is a misrepresented statistic. The paper behind this statistic (Cook et al. 2013) states that only 32.6% of all articles on climate change expressed any opinion on human-induced warming in the abstract. Of this 32.6%, 97% supported the theory. However, the remaining 67.4% of the articles analysed in the study did not articulate an opinion for or against human-induced warming in the abstract.

Both sides argue unethical conduct from the other side, driven by perceived conflicts of interest. Advocates often accuse sceptics of being funded by the fossil fuel industry or other financially interested parties. Sceptics argue that there is a conspiracy that scientists' claims of anthropogenic climate change are a bid to gain governmental control over energy consumption. One group of sceptics hacked email servers at a leading institution for climate research and posted (misrepresented) snippets of emails on the Internet to support their conspiracy theory. Neither side of the debate is innocent.

The stakes of the debate and therefore the emotions of those debating are high. From the advocates' point of view—the stakes are the wellbeing of the planet. They (like we) believe that failure to act will lead to severe consequences for humankind. However, to act is unlikely to be a minor undertaking. Sceptics are reluctant to make changes of the order of magnitude believed necessary by advocates based on what they believe to be uncertain science.

It is understandable therefore that the debate is so fierce and sensitive. However, at the core, it is a debate over scientific evidence. This chapter does not explore who said what or the motivations of sceptics or advocates. It presents the scientific evidence for and against anthropogenic (human caused) climate change and attempts to address both sides of the argument with transparency. The chapter begins by introducing the concept of the Earth system. It then presents the core evidence for anthropogenic climate change. Those who do not believe in anthropogenic climate change generally fall into one of three categories: those who do not believe the climate is changing; those who believe the climate is changing but do not believe that this is caused by human activity; and those who believe human activity is changing the climate but do not agree that this is important. This chapter goes on to address the key arguments made against anthropogenic climate change under these three categories.

2.2 Earth as a System

The sum of the planet's physical, chemical, and biological processes is known as the Earth system. Everything in the Earth system belongs to one of four subsystems or "spheres": the geosphere (land), hydrosphere (water), atmosphere (air), and biosphere (life). The four spheres are interconnected by Earth-system processes—such as evaporation, transpiration, and photosynthesis—that store, transfer, and transform matter and energy according to the laws of physics and chemistry (Skinner and Murck 2011). The relationships between the processes are complex. There are many feedback loops—responses to external influences which can dampen or amplify change. Feedback loops can lead to tipping points—points of rapid, runaway, irreversible change—even when the original perturbance is removed (Scheffer et al. 2001; Lenton et al. 2008). For example:

> People emit carbon to the atmosphere (an external influence). Carbon dioxide is a greenhouse gas which means is traps heat in the atmosphere. As the atmosphere heats up, this causes ice to melt leaving behind dark blue ocean. Ice is reflective. Dark blue ocean is not. This means that more heat can be absorbed by Earth's surface (assuming other factors affecting Earth's albedo do not change). More heat means more ice melts. Earth's reflectivity reduces further, and the feedback loop continues.

This is only one example. There are many other feedback loops that affect climate change and other Earth-system processes. Some, like the melting ice, are positively reinforcing, i.e. they accelerate change. Other feedback loops help to stabilize Earth-system processes. These are called negative feedback loops. The risk that we face today is that we may reach a tipping point—where the positive feedback loops accelerate change—resulting in rapid and possibly irreversible change, beyond our control. The state of the Earth system can change very rapidly. For example, the transition from the last glacial period, the Younger Dryas, to the current interglacial, is thought to have happened over only a few decades. In Greenland, temperature changes of as much as 10 °C per decade are believed to have occurred during this period (Severinghaus et al. 1998).

The Earth system can operate in many different states. Each state is typically separated by a relatively short period of rapid change. Average global temperature is not the only variable that changes from one environmental state to another. The chemical composition of the atmosphere, the amount of energy the Earth's surface receives from the Sun, the ratio of ocean to land area of Earth's surface, and the number and type of species inhabiting Earth are all examples of variables that can differ between different environmental states.

2.3 We Are at Risk of Changing the State of the Planet

Since the industrial revolution, human emissions of CO_2 have accelerated exponentially. Since humans evolved, CO_2 levels have been approximately 350 ppm. The atmosphere currently contains more than 400 parts of carbon dioxide (CO_2) per million parts of atmosphere (ppm). This is higher than any level measured since we began measuring the amount of carbon dioxide in the atmosphere. The rate of increase in CO_2 emissions correlates with the rate of increase in CO_2 concentration. Approximately half of all anthropogenic emissions remain in the atmosphere. There is *very high confidence*[1] that the amount of CO_2, and other greenhouse gases (GHGs) including methane, and nitrous oxide in the atmosphere is higher than it has been in 800,000 years (IPCC 2013). To put this into context, homo sapiens are believed to have evolved 300,000 years ago. Humans have never experienced such high concentrations of CO_2. More alarming to scientists than the high concentration of greenhouse gases is the rate of increase of these gases in the atmosphere. CO_2 levels are currently increasing at a rate between 100 and 200 times faster than the rate of increase that occurred at the end of the last Ice Age. There are other periods in history where CO_2 levels have increased rapidly—at rates of the same order of magnitude as rates of increase today. These past events have been highly destructive to life—causing mass global extinctions—i.e. more than 75% of the existing species on Earth went extinct in a short period of time.

It is not the CO_2 in the atmosphere per se that is concerning. Rather, concerns are for the anticipated impacts to the Earth system that this could cause. There has been a very strong correlation between CO_2 and global average temperatures over the last 800,000 years (McInnes 2014) (see Fig. 2.1). It is *virtually certain*[1] that globally, the troposphere has warmed since the mid-1900s (IPCC 2013). It is *extremely likely* that more than half the warming that has been recorded for average surface temperatures from 1950 to now occurred because of human activity (IPCC 2013).

It is not certain what increased average temperatures would mean for humanity, but predictions are not optimistic. It is *likely*[1] that increased temperatures will lead to global average increase in rainfall and that the rainfall distribution will change so that wet areas become wetter and dry areas become drier. It is *very likely* that the Atlantic Meridional Overturning Circulation (AMOC), the global flow of oceans that is an important component of Earth's climate system, will weaken, although it is *very unlikely* that it will collapse altogether this century. It is *very likely* that arctic sea ice will continue to shrink and thin and that global glacier volume will continue to decrease. It is *very likely* that sea levels will continue to rise and that the rate of sea level rise will increase. The likelihood of future increases to the frequency and/or intensity of extreme weather events ranges from *more likely than not* (for tropical

[1] The terms used to describe likelihood correspond to scientific probabilities as follows: "virtually certain"—>99% "extremely likely" >95%, "very likely" >90%, "likely" >66%, "more likely than not" >50%, and "very unlikely" <10%. The term "very high confidence" conveys a 9/10 chance of being correct.

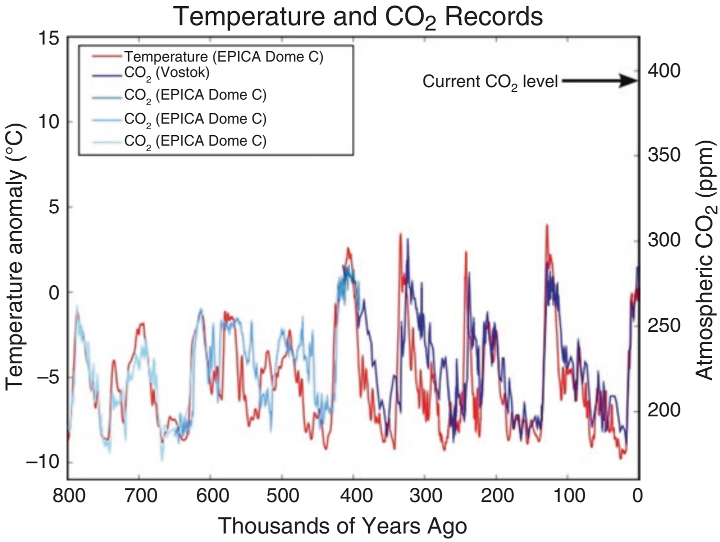

Fig. 2.1 Average change in temperature with respect to average Holocene temperatures and atmospheric concentration of CO_2. (McInnes 2014, CC BY-SA 3.0, CC BY-SA 3.0: Creative Commons License allows reuse with appropriate credit)

cyclone activity) to *virtual certainty* (for warmer days and nights over most land areas) (Stocker et al. 2013; IPCC 2013).

2.3.1 Understanding CO_2 and Temperature

Figure 2.1 shows 800,000 years of CO_2 and temperature data, yet we have only been recording CO_2 levels since 1950. The estimates of past CO_2 levels in the atmosphere before 1950 are based on measurements of ancient air that is stored in glacial ice. The ancient air samples can also be used to estimate past temperatures because the composition of air changes with changing temperatures. Other independent evidence is then used to support ice core data. For example, the distance between tree rings indicates tree growth rate which is influenced by both temperature and CO_2 levels. There is tree ring data spanning 10,000 years which, until recent years, showed a strong correlation with the ice-core data. Fossilized leaves can be used as another indication of past CO_2 levels. There is approximately 400,000 years of leaf fossil data, and this correlates closely with ice core data. Lake and ocean sediments change with temperature, rainfall, and snowfall and can also be used to support ice core data (NOAA 2018).

Ice layers accumulate over hundreds of thousands of years which protect ancient ice from melting, thus storing important information about the past climate. However, heat from bedrock below the ice slowly melts the oldest ice so that until recently, ice core data had only been found dating back 800,000 years.[2] To determine CO_2 levels and temperatures prior to 800,000 years ago, proxy data such as isotopes found in shells and fossils of ancient marine organisms have been used. This data provides insight into the climatic conditions for the entire Phanerozoic period—i.e. the geological eon beginning 540 million years ago that we are still in today, albeit at a low resolution (Veizer et al. 1999; Berner 1991; Berner and Kothavala 2001; Crowley and Berner 2001; Royer et al. 2004).

There have been several analyses of CO_2 and temperature data for the Phanerozoic period. Of these, most found a positive correlation between CO_2 and temperature, i.e. low CO_2 levels overlapped with extensive glaciations and high CO_2 levels did not (Berner 1991, Berner and Kothavala 2001, Crowley and Berner 2001, Royer et al. 2004). One study did not find a positive correlation between the two (Veizer et al. 2000). However, it was found later that the temperature proxy data used in this study had not been corrected for seawater pH. Once the data had been updated, the same positive correlation could be seen (Royer et al. 2004).

One of the arguments put forwards by sceptics is that the Phanerozoic CO_2 and temperature data are not coupled. The basis of this argument is that one period of glaciation that occurred during this period does not appear to correlate with low CO_2 levels. This glaciation, known as the late Ordovician glaciation, occurred approximately 440 million years ago. Some sceptics have used this data to suggest that this period of glaciation coincided with very high levels of CO_2 somewhere between 2400 and 9000 ppm (Berner and Kothavala 2001).

The correlation between CO_2 and temperature found for the Phanerozoic period pertains to *extensive* periods of glaciation only. This is not because the data shows that shorter period of glaciation occurred during high levels of CO_2. It is because the data is too coarse to draw any conclusions about shorter periods of glaciation or any short period at all. Extensive periods of glaciation do correlate with low levels of CO_2.

The CO_2 data available for this period is in intervals of approximately 10 million years (Royer et al. 2004). In contrast, the late Ordovician glaciation is thought to have lasted less than 1 million years (Royer et al. 2004). Only one datum exists close to the period of the glaciation (Royer 2006). This proxy data point cannot be more accurately dated than a point in time between 450 and 443 million years ago. It is conceivable that the CO_2 levels dropped during the Ordovician glaciation. There is geochemical evidence to support this theory. Carbon cycle modelling for this period suggests that CO_2 levels may have dropped to 3000 ppm during the glaciation (Kump et al. 1999).

Even at 3000 ppm it may seem unlikely that a period of glaciation could occur. Current CO_2 levels are a little over 400 ppm, and glaciers and arctic sea ice are melting. However, CO_2 is only one driver of average temperature. There are other factors

[2] Recently ancient ice, approximately 2.7 million years old, has been discovered. Voosen, P. 2017. Record-shattering 2.7-million-year-old ice core reveals start of the Ice Ages. *Science.* There is not yet enough ice to draw strong conclusions from the findings. However, scientists are hopeful that this discovery will lead to a greater understanding of ancient climatic conditions.