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OVERVIEW

Consider a brief overview of the issues to be surveyed in the following chapters. This overview outlines observed and expected changes, our ability to attribute observed trends and events to anthropogenic climate change, the level and reasons for the uncertainties involved in quantifying both observed and projected changes, and the very diverse timescales of the major processes involved.

The first three chapters address the basics: What are greenhouse gases and how do they lead to warming? How and why does the atmospheric warming vary in time and space (both as a function of latitude and height)? And finally, sea level rise. Beginning with greenhouse gases, the blue line in Figure 1.1a shows the iconic Mauna Loa CO_2 record collected since 1958, preceded by an ice-core-based reconstruction. CO_2 concentration has been at 280 ppm for over 10,000 yr, since the last ice age, and has therefore increased by about 50% so far, at an unprecedented speed. There is, of course, no doubt that CO_2 is increasing and that the increase is attributable to the anthropogenic burning of fossil

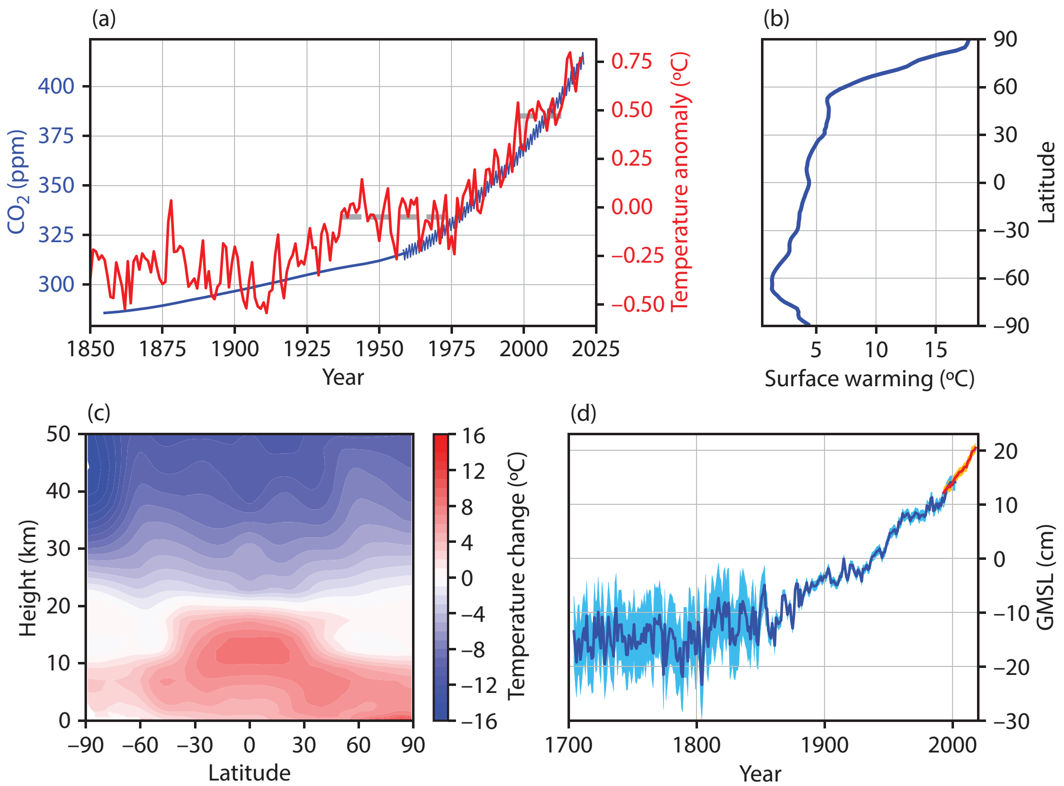


Figure 1.1: Greenhouse effect, warming, and sea level rise.
(a) Atmospheric CO_2 concentration (blue) and global mean surface temperature anomaly (in red, defined as the deviation from the mean over 1961–1990) since 1850. Also shown by gray dashed lines are two "hiatus" periods of *seemingly* reduced rates of warming. (b) The projected surface warming over the 21st century in an RCP8.5 scenario in a climate model, as a function of latitude, showing a very pronounced polar (mostly Arctic) amplification. (c) Projected atmospheric temperature changes over the 21st century as a function of altitude and latitude, showing a tropospheric warming and stratospheric cooling in the RCP8.5 scenario. (d) Estimated global-mean sea level anomaly since 1700 (blue line) and the estimated uncertainty (light-blue shading). In red and orange: the satellite record since 1993.

fuel. Once in the atmosphere, we will see that it will take thousands of years for the CO_2 to naturally decline after anthropogenic emissions are eliminated. Chapter 2 addresses the question of how greenhouse gases trap heat and lead to warming, both on a molecular level and by examining the Earth global energy balance. These are ideas that have been well understood for a while now. The warming due to greenhouse gas increase is explored in chapter 3. The red line in Figure 1.1a shows that the globally averaged surface temperature anomaly (defined as the deviation from a reference value, in this case the mean over 1961–1990) has warmed so far by over 1 °C. Future climate projections rely on estimates of future greenhouse gas concentrations, referred to as Representative Concentration Pathways (RCPs) and followed by a number indicating the expected enhancement in radiative heating. We discuss these scenarios in section 2.1 and note briefly now that RCP8.5 is what one might think of as a business-as-usual scenario in which CO_2 concentration increases to a very high value of over 1000 ppm by year 2100. While one hopes that such a high future greenhouse gas concentration is not a realistic scenario, it allows us to clearly understand climate change trends and mechanisms that may be more difficult to identify in less severe scenarios. Figure 1.1b shows that the projected surface warming under RCP8.5 is strongly amplified toward the poles (especially the Arctic), while Figure 1.1c shows that the stratosphere is projected under the same scenario to cool significantly above an altitude of about 20 km, while the troposphere warms. Polar amplification and stratospheric cooling are already observed today, and we will examine several mechanisms that are responsible for these signals. We will also see that even at the present level of CO_2, additional warming would have occurred if not for the cool, deep ocean, which takes hundreds of years to warm in response to the enhanced greenhouse forcing. While CO_2 has increased monotonically, the warming of the global mean surface temperature seems to have paused during 1940–1970 or so and during 1998–2013, as shown by the horizontal dashed lines in Figure 1.1a. We will show that such seeming "hiatus" periods in the increase in global mean surface temperature are an expected consequence of anthropogenic warming in the presence of natural climate variability.

One of the most consequential results of ocean warming and of the expected melting of land-based ice is sea level rise, as analyzed in chapter 4 and shown in Figure 1.1d. Global mean sea level has increased by some 30 cm over the past 150 yr, is currently increasing at about 3.5 mm/yr, and is projected to rise by up to a meter by 2100. Many processes are responsible for sea level rise, from the expansion of warming ocean water to land-based ice melting. Furthermore, sea level rise is expected to vary from region to region, and we will discuss the many mechanisms involved, from wind and atmospheric pressure changes, to the gravitational effect of melting ice over Greenland and Antarctica, and more. The timescales of the processes involved vary from a near-instantaneous

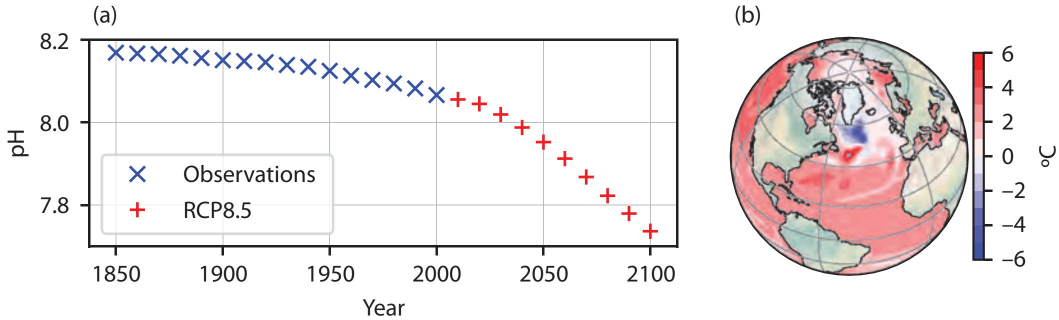


Figure 1.2: Ocean acidification and circulation.
(a) Observed mean surface ocean pH from 1850 to 2000 (blue), followed by projected pH to 2100 in the RCP8.5 scenario (red). (b) Projected sea surface temperature change over the 21st century in the RCP8.5 scenario, showing an overall warming, yet with a local cooling in the northern North Atlantic due to the projected collapse of the ocean overturning circulation.

response (e.g., to changes in atmospheric pressure or ocean currents) to hundreds of years (warming of the deep ocean, melting in Greenland), to many thousands (significant melting of East Antarctica), with uncertainty levels typically higher for processes with longer timescales.

Two more ocean-centered issues are next examined, beginning with ocean acidification in chapter 5 and then the possible collapse of the meridional overturning ocean circulation in chapter 6. Ocean acidification is referred to as "the other global warming problem." The absorption by the ocean of about a quarter of the anthropogenically emitted CO_2 (with another quarter absorbed by the land biosphere) has significantly reduced the warming experienced so far. Yet Figure 1.2a shows that as a result, ocean pH, the measure of seawater acidity, already decreased from 8.16 to 8.06, which implies a significant increase of 25%(!) in the concentration of H^+ ions in the ocean. We will examine the basic carbonate chemistry behind ocean acidification, how it may affect the deposition of calcium carbonate structures by oceanic organisms, and how atmospheric CO_2 can eventually decline once emissions are significantly reduced, on a timescale of thousands of years. While there is little uncertainty involved in assessing expected ocean pH for a given atmospheric CO_2 level, the response of ocean biology is complex and is still being studied.

Chapter 6 discusses how the oceanic meridional circulation, which carries heat poleward and contributes to the warmth of the high-latitude North Atlantic, may collapse in a global warming scenario over the next century or so. The circulation collapse is expected to contribute to a regionally reduced warming and even cooling in the northern North Atlantic, as shown in the model projection of Figure 1.2b, as well as to other disruptions to the current state of the ocean. We will analyze how a gradual CO_2 increase may lead to an abrupt ocean circulation response, explaining in the process the concept of climate *tipping points*.

Returning to the atmosphere in the next two chapters, we address two issues surrounded by a larger degree of uncertainty: clouds and hurricanes. In chapter 7 we study clouds, believed to be the main source of uncertainty in global warming projections and one of the main reasons that the uncertainty in global warming projections has not decreased over the past four decades. Unlike the discussion of climate change issues in other chapters, the focus of this chapter is not explaining an observed or projected change but rather making it clear why clouds are a source of such large uncertainty in our climate projections. Clouds have a most significant effect on climate due to both their reflectivity of sunlight, which has a cooling effect, and their trapping of heat emitted by the Earth surface, contributing to the greenhouse warming effect. Figures 1.3a,b show the projected change in clouds over the 21st century in the RCP8.5 scenario in two different climate models. The two models clearly calculate a very different cloud response, demonstrating the model disagreement and therefore the uncertainty in future projections of clouds. This disagreement in the simulation of cloud cover also leads to a very different warming projected by these two models, and we will explain why the representation of clouds in climate models involves such a large uncertainty. The subject of clouds allows us to also explore that of atmospheric convection, which comes up repeatedly in the discussion of many global warming–related issues. Following that, the response of hurricanes to global warming, both observed and projected for a future climate, is analyzed in chapter 8. Figure 1.3c shows the estimated number of Atlantic hurricanes over the past 140 yr. It is difficult to identify a trend in these data, and it turns out that there is currently no reliable and well-understood mechanism that can be used to project future changes to the *number* of storms. We discuss the formation mechanism of hurricanes, how it depends on the upper ocean temperature, and why the *magnitude* of hurricanes may be expected to increase in a warmer climate. We also analyze the observed record and examine the many uncertainty factors involved in the projection of future hurricane magnitudes.

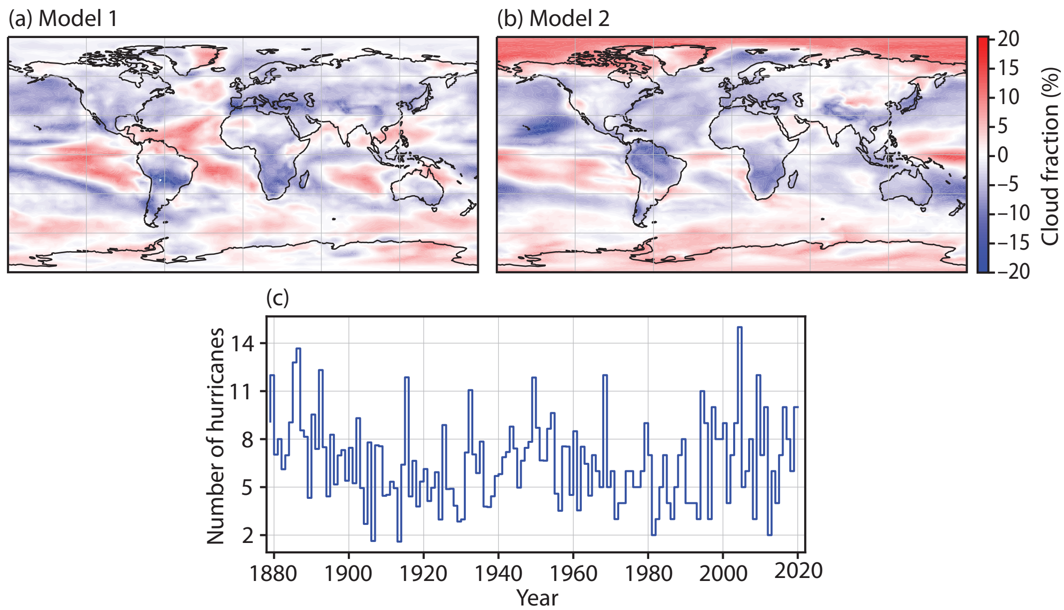


Figure 1.3: Clouds and hurricanes.
(a,b) Projected change in cloud cover due to greenhouse forcing, from a preindustrial state to 2100 in the RCP8.5 scenario, for two different climate models, demonstrating the large uncertainty in simulating clouds in climate models. (c) Estimated number of hurricanes over the North Atlantic as a function of year.

The following three chapters deal with the cryosphere: Arctic sea ice, ice sheets over Greenland and Antarctica, and mountain glaciers. Chapter 9 explains the processes and powerful feedbacks behind the dramatic and well-observed decline of summer Arctic sea ice over the past few decades (but not of sea ice near Antarctica, interestingly). This decline is seen in Figure 1.4a, and the same processes and feedbacks may lead to an even more dramatic decline over the next few decades. We also discuss ways of differentiating between a sea ice melt trend due to anthropogenic climate change and trends due to natural variability. Possible mechanisms and feedbacks that may lead to a significant reduction of the ice mass of the large ice sheets of Greenland and Antarctica are presented in chapter 10. Such a reduction can cause a further rise of sea level by many meters over a timescale of hundreds to thousands of years and involves a large degree of uncertainty. There is the (quite uncertain) potential for rapid changes as well, and we explain the mechanisms that may lead to such a tipping point behavior. This is followed by an analysis in chapter 11 of one of the more iconic

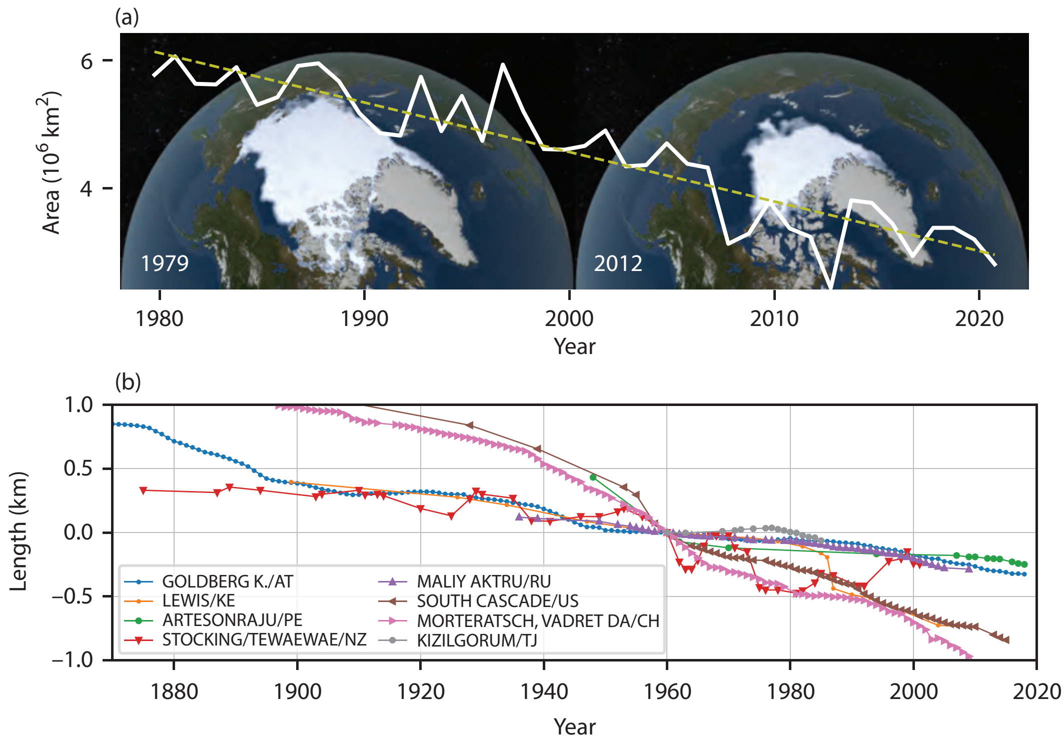


Figure 1.4: The cryosphere.
(a) The yearly minimum (September) Arctic sea ice area as a function of year over the satellite era, superimposed on NASA images of sea ice cover the first year of satellite data, 1979, and a year of a particularly small sea ice area, 2012. (b) Records of glacier length for a few mountain glaciers, relative to their length in 1960.

consequences of the already observed global warming: the retreat of mountain glaciers, as seen in Figure 1.4b. These changes are already occurring, and we will see that the retreat over the past three or so decades can be clearly attributed to anthropogenic global warming. We explain the processes behind this decline and the relevant dynamics of mountain glaciers that underlie their observed and projected decline.

We conclude with three chapters on possible consequences of climate warming, involving changes to droughts and precipitation, heat waves and forest fires. We review in chapter 12 the types and causes of prolonged droughts, as demonstrated in Figures 1.5a,b, showing how La Niña events in the equatorial east Pacific can lead to California droughts in a climate model. This is then used to consider why droughts might change in the future and why such a prediction

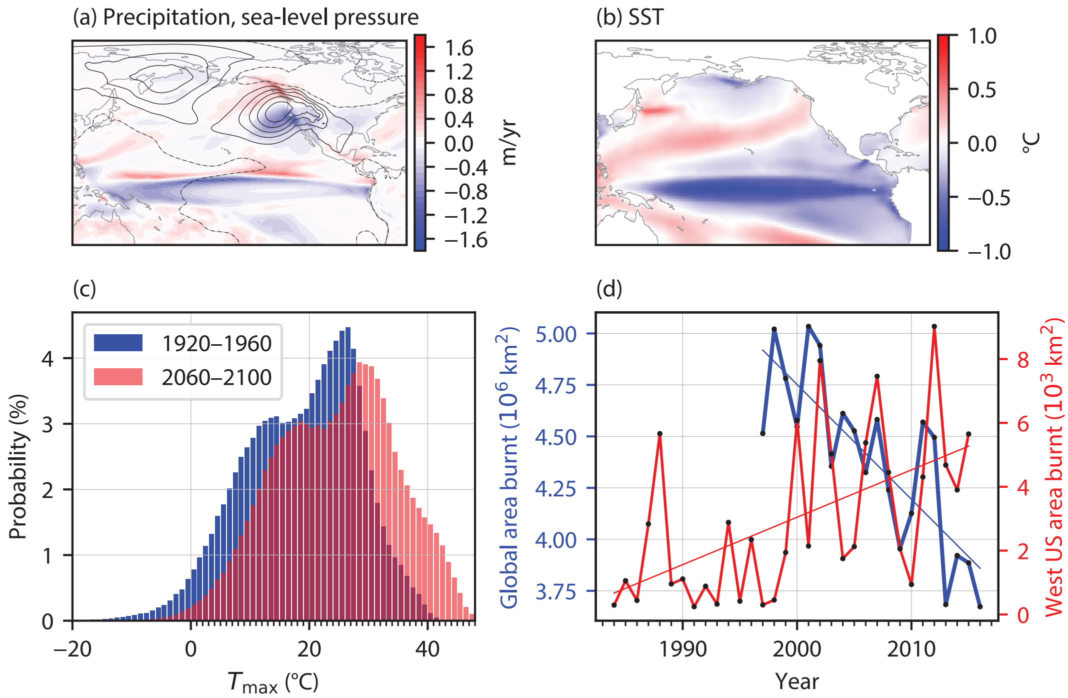
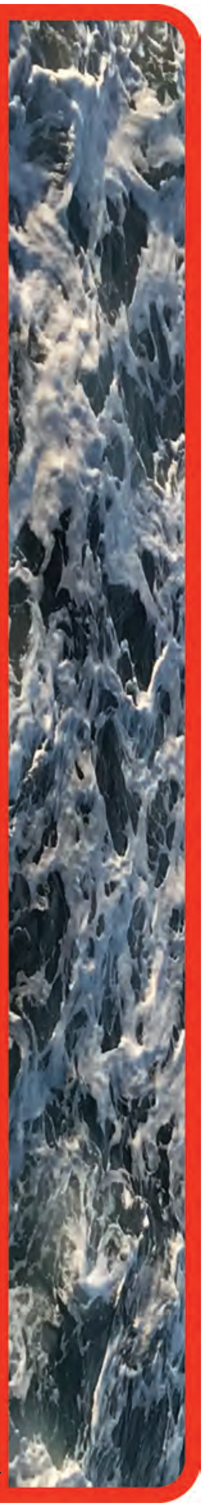


Figure 1.5: Droughts, heat waves, and forest fires.
(a,b) An analysis of droughts in a climate model. Colors in (a) show the precipitation anomaly during January drought years over California, with the blue area over California and off-coast there indicating lower precipitation than normal. The black contour lines show a high sea level atmospheric pressure anomaly that typically occurs above drought conditions (contour interval is 1 hPa; zero contour is dash-dot). (b) Sea surface temperature anomaly during these California drought years, showing a La Niña–like cold sea surface temperature (see box 8.1) over the equatorial Pacific and demonstrating how sea surface temperature anomalies drive remote drought conditions. (c) Heat waves in a warming climate. The probability of occurrence of maximum daily temperatures over the great plains in the United States at the beginning of the 20th century (blue) vs at the end of the 21st century in the RCP8.5 scenario (red). The shift to larger daily maximum temperatures is an example of projected changes to the characteristics of heat waves. (d) Forest fires. The red curve shows the increasing burnt area over the western United States over the past decades, and the blue curve shows a decrease in the global burnt area since the 1990s.

is still uncertain. We will see how the severity of past droughts can be reconstructed, helping to put current drought events into perspective, and we will model the processes that control soil moisture during droughts. We then analyze two test cases, the Sahel and Southwest United States, and explicitly demonstrate the uncertainty in future projections of droughts. Finally, we consider projections for precipitation changes from three perspectives. First, we discuss the projection that the Hadley meridional atmospheric circulation—of air rising near the equator and sinking at about 30° north and south—might expand poleward. The expansion has possible consequences to the location of desert bands that tend to be located under the subsiding part of the Hadley circulation. Second, we attempt to understand the projection that precipitation changes will follow a pattern of *wet getting wetter and dry getting drier* over large areas of the globe, as well as the limitations of this overall projected pattern, which does not seem robust over land areas. And finally, we examine projections for precipitation extremes and explain why there is a robust expectation for more precipitation to occur in heavy precipitation events in a warmer climate.

Heat waves are studied in chapter 13. These are weather events, and are therefore much shorter than droughts but share some of their physical mechanisms and characteristics. Figure 1.5c shows how the probability of occurrence of a high maximum daily temperature dramatically increases in model projections from the early 20th century (blue bars) to late in the 21st century (red). We demonstrate how the statistics of heat waves may change and what this can teach us about their dynamics in a warmer climate. We conclude with the subject of forest fires (chapter 14). Observations suggest a recent increase in fires over the western United States, for example, as seen in Figure 1.5d (red line), although global fire area has decreased over the past couple of decades (blue). We address factors affecting forest fires and different ways in which humans can affect fires via both climate- and non-climate-related influences. While we do understand qualitatively how fires depend on these many different factors, the issues involved are sufficiently complex that the only way to attempt to differentiate the effect of anthropogenic climate change from other anthropogenic effects and from natural climate variability is statistical analysis, resulting in very significant uncertainty. We discuss, as specific examples, fires in the western United States and Australia, as well as on a global scale, and attempt to identify many of the uncertainties involved.

As we move into the detailed analysis of these issues that arise in global warming science, we keep in mind the following questions: *What* has been observed or what is projected? *Why* do these changes occur, or why are they expected? What is the *timescale* in which these changes operate? What are the *uncertainty levels*, and *sources of uncertainty*?



1.1 WORKSHOP

A Jupyter notebook with the workshop and corresponding data file are available; see https://press.princeton.edu/global-warming-science.

Go over and solve the first python notebook with an introduction to programming and a very brief review of some basic math concepts that are used later in the course.

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