Chapter 9 — Key Findings and Recommendations

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9.1 INTRODUCTION

Paleoclimatic data provide a highly informative if incomplete history of Arctic climate. Temperature history is especially well recorded, and it commonly allows researchers to accurately reconstruct changes and rates of changes for particular seasons. Precipitation (rain or snow) and the extent of ice on land and sea are some of the many other climate variables that have also been reconstructed. The data also provide insight to the histories of many possible causes of the climate changes and feedback processes that amplify or reduce the resulting changes. Comparing climate with possible causes allows scientists to generate and test hypotheses, and those hypotheses then become the basis for projections of future changes.

Arctic data show changes on numerous time scales and indicate many causes and important feedback processes. Changes in greenhouse gases appear to have been especially important in causing climate changes [sections 4.4; 5.4.1; 5.4.4, 6.4.1; 6.4.2]. Global climate changes have been notably amplified in the Arctic [section 5.5.2], and warmer times have melted ice on land and sea [chapter 8].[1]

9.2 SUMMARY OF KEY FINDINGS

Chapter 5 Temperature and Precipitation

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[1] Statistically valid confidence levels often can be attached to scientific findings, but commonly require many independent samples from a large population. Such a standard can be applied to paleoclimatic data in only some cases, whereas in other cases the necessary archives or interpretative tools are not available. However, expert judgment can also be used to assess confidence. The key findings here cannot all be evaluated rigorously using parametric statistics, but on the basis of assessment by the authors, all of the key findings are at least "likely" as used by the Intergovernmental Panel on Climate Change (more than 66% chance of being correct); the authors believe that the most of the findings are "very likely" (more than a 90% chance of being correct).

The Arctic of 65 million years ago (Ma) was much warmer than recently; forests grew in all land regions and neither perennial sea ice nor the Greenland Ice Sheet were present. Gradual but bumpy cooling has dominated since, with falling atmospheric CO_2 concentration apparently the most important contributor to the cooling, although with possible additional contributions from changing continental positions and their effect on atmospheric or oceanic circulation. Warm "bumps" during the general cooling trend include the relatively abrupt Paleocene-Eocene Thermal Maximum about 55 Ma, apparently caused by CO_2 release, and a more gradual warming in the middle Pliocene (about 3 Ma) of uncertain cause.

Around 2.7 Ma cooling reached the threshold for extensive development of continental ice sheets throughout the North American and Eurasian Arctic. Periodic growth and shrinkage of the ice during tens of thousands of years were directly controlled by periodic changes in northern hemisphere sunshine caused by features of Earth's orbit. Recent work suggests that, in the absence of human influence, the current interglacial would continue for a few tens of thousands of years before the start of a new ice age. The large temperature differences between glacial and interglacial periods, although driven by Earth's orbital cycles and the globally synchronous response, reflect the effects of strong positive feedbacks, such as changes in atmospheric CO_2 and other greenhouse gases and in the extent of reflective snow and ice.

Interactions among the various orbital cycles have caused small differences between successive interglacials. During the interglacial about 130–120 thousand years ago (ka), the Arctic received more summer sunshine than in the current interglacial, and temperatures in many places were consequently 4° to 6°C warmer than recently, which reduced ice on Greenland (Chapter 7), raised sea level, and melted small glaciers and ice caps.

The cooling into and warming out of the most recent glacial were punctuated by numerous abrupt climate changes, with millennial persistence of conditions between jumps requiring years to decades. These events were very large around the North Atlantic but much smaller elsewhere in the Arctic and beyond. Large changes in the extent of sea ice in the North Atlantic were probably responsible, linked to changes in regional and global patterns of ocean circulation. Freshening of the North Atlantic also favored formation of sea-ice.

These abrupt changes also occurred in the current interglacial (the Holocene), but they ended as the Laurentide Ice Sheet on Canada melted away. Arctic temperatures in the Holocene broadly responded to orbital changes with warmer temperatures during the early to middle Holocene when there was more summer sunshine. Warming generally led to northward migration of vegetation and to shrinkage of ice on land and sea. Small oscillations in climate during the Holocene, such as the Medieval Climate Anomaly and the Little Ice Age, were linked to variations in the sun-blocking effect of particles from explosive volcanoes and perhaps to small variations in solar output or in ocean circulation or other factors. The warming after the Little Ice Age began for largely natural reasons, but there is now high scientific confidence that human contributions, and especially increasing concentrations of CO_2, have come to dominate the warming (Jansen et al., 2007).

Comparison of summertime temperature anomalies for the Arctic and for lower latitudes, averaged over at least millennia for key climatic intervals of the past, shows that Arctic changes were threefold to fourfold larger than those in lower latitudes. This more pronounced response applies to intervals that were both warmer and colder than in recent decades. Arctic amplification of temperature changes thus appears to be a consistent feature of the Earth system.

Chapter 6 Rates of Change

Climate changes have many causes and occur at different rates sustained for different intervals. The changing atmospheric composition, and atmospheric and oceanic circulation linked to tectonic processes during tens of millions of years have shifted the Arctic from ice-free winters to icy summers. Features of Earth's orbit acting for tens of thousands of years have rearranged sunshine on the planet and paced the growth and shrinkage of great ice-age ice sheets. Anomalously cold single years have resulted from the influence of large, explosive volcanoes, with slightly anomalous decades in response to the random variations in the frequency of occurrence of such explosive volcanoes..

The local effects of these changes, as observed in Greenland or more generally around the Arctic, yield trends such that more-persistent forcings have produced larger changes at a lower average rate. Relative to these general trends, abrupt climate changes linked to shifts in oceanic conditions of the North Atlantic produced anomalously large and rapid temperature changes near the North Atlantic but relatively small average global temperature changes. And, relative to these general trends, human-linked perturbations of the most recent decades do not appear anomalously rapid or large, but changes projected as a part of the IPCC process can become anomalously large and rapid.

Interpretation of these observations is complicated by lack of a generally accepted way of formally assessing the effects or importance of size versus rate versus persistence of climate change. The report here relied much more heavily on ice-core data from Greenland than would be ideal in assessing Arctic-wide changes. Great opportunities exist for generation and synthesis of other data sets to improve and extend the results here, using the techniques described in this report. If widely applied, such research could remove the over-reliance on Greenland data.

Chapter 7 The Greenland Ice Sheet

Paleoclimate data show that the Greenland Ice Sheet has changed greatly with time and has affected global sea level. Physical understanding indicates that many environmental factors can force changes in ice-sheet size. Comparing histories of important forcings with ice-sheet size implicates cooling as causing ice-sheet growth, warming as causing shrinkage, and sufficiently large warming as causing loss. The evidence for temperature control is clearest for temperatures similar to or warmer than those occurring in the last few millennia. The available evidence shows less ice when snowfall was higher, indicating that snowfall rate is not the leading control on ice-sheet size. Rising sea level tends to float marginal regions of ice sheets and force their retreat, so the generally positive relation between sea level and temperature means that, typically, both have pushed the ice sheet in the same direction. However, for some small changes during the most recent millennia, marginal fluctuations in the ice sheet have been opposed to those expected from local relative sea-level forcing but in the direction expected from temperature forcing. This, plus the tendency for shrinkage to pull ice-sheet margins out of the ocean, indicate that sea-level change has not been the dominant forcing at least for temperatures similar to or greater than those of the last few millennia.

Histories of ice-sheet volume in fine time detail are not available, but the limited paleoclimatic data at least agree that short-term and long-term response to temperature change have been in the same direction. The best estimate from paleoclimatic data is thus that warming shrinks the Greenland Ice Sheet, and warming of a few degrees is sufficient to cause ice-sheet loss. Figure 7.13 shows a threshold for ice-sheet removal from sustained warming of 5°C, with a range of uncertainties from 2° to 7°C, but tightly constrained numerical estimates are not available, nor are rigorous error bounds, and the available data poorly constrain the rate of loss. Numerous opportunities exist for additional data collection and analyses that would reduce the uncertainties.

Chapter 8 Arctic Sea Ice

Geological data indicate that the history of Arctic sea ice is closely linked with temperature changes. Sea ice in the Arctic Ocean may have appeared in response to long-term cooling as early as 46 Ma. Year-round sea ice in the Arctic possibly developed as early as 13–14 Ma, before the opening of the Bering Strait at 5.5 Ma. Nevertheless, extended seasonally ice-free periods probably occurred until about 2.5 Ma. They ended with a large increase in the extent and duration of sea-ice cover that more or less coincided with the onset of extensive glaciation on land (within the considerable dating uncertainties). Some data suggest that ice reductions marked subsequent interglacials and that the Arctic Ocean may have been seasonally ice-free during the warmest events. For example, reduced-ice conditions are inferred for the last interglacial and the onset of the current interglacial, about130 and 10 ka .

Limited data suggest poorly understood variability in ice circulation for centuries to millennia, but without strong periodic behavior on these time scales. Historical observations suggest that ice cover has been shrinking since the late 19th century, and that the decline has accelerated during the last several decades. This accelerated rate exceeds natural declines typical of at least the most recent few millennia. This ice loss appears to be unrelated to natural climatic and hydrographic variability on decadal time scales or to multi-millennial orbital insolation changes.

9.3 RECOMMENDATIONS

Paleoclimatic data on the Arctic are generated by numerous international investigators who study a great range of archives throughout the vast reaches of the Arctic. The value of this diversity is evident in this report. Many of the key results of this report rest especially on the outcomes of community-based syntheses, such as the CAPE Project, and on multiply replicated and heavily sampled archives, such as the central Greenland deep ice cores. Results from the ACEX deep coring in Arctic Ocean sediments were appearing as this report was being written; these results were quite valuable and will become more so with synthesis and replication, including comparison with land-based as well as marine records. The number of questions answered, and raised, by this one new data set shows how sparse the data are on many aspects of Arctic paleoclimate change. ***We recommend that future research maintain and expand the diversity of investigators, techniques, archives, and geographic locations, while promoting development of community-based syntheses and multiply-replicated, heavily-sampled archives; only through breadth and depth can the remaining uncertainties be reduced while confidence in the results is improved.***

The questions asked of this study by the CCSP are relevant to public policy and require answers. The answers provided here are, we hope, useful and informative. However, we recognize that despite the contributions of numerous community members to this report, in many cases a basis was not available in the refereed scientific literature to provide answers with the accuracy and precision desired by policymakers. ***We recommend that members of the***

Arctic paleoclimatic community formulate future research activities to address in greater detail the policy-relevant questions that motivated this report.

Paleoclimatic data provide very clear evidence of past changes in important aspects of the Arctic climate system. The ice of the Greenland ice sheet, smaller glaciers and ice caps, the Arctic Ocean, and soils are shown to be vulnerable to warming, and Arctic ecosystems are strongly affected by changing ice and climate. National and international studies generally project rapid warming in the future. If this warming occurs, the paleoclimatic data indicate that melting of ice and associated effects will follow, with implications for ecosystems and economies. ***We recommend that policymakers and science managers use the results presented here in design of monitoring, process, and model-projection studies of Arctic change and linked global responses.***

Highlights of Key Findings

- Arctic climate has changed greatly during the last 65 million years and before, at highly varying rates and in response to many causes, with changing atmospheric carbon-dioxide concentrations especially important in controlling temperature.
- Arctic temperature changes have been larger than correlative globally averaged changes, by approximately threefold to fourfold in both warmer and colder times, in response to processes still active in the Arctic.
- Arctic temperatures have changed greatly but slowly in response to long-lasting causes and by lesser amounts but more rapidly in response to other causes.

Human-forced changes of the most recent decades do not appear notably anomalous in rate or size for their duration when they are compared with these natural changes, but projections for future human-caused changes include the possibility of anomalously large and rapid changes.

- The Greenland Ice Sheet has consistently grown with cooling and shrunk with warming, and a warming of a few degrees (about 5°C, with uncertainties between about 2° and 7°C) or more has been sufficient to completely or almost completely remove the ice sheet if maintained long enough; the rate of that removal is poorly known. Reduction in the size of the Greenland Ice Sheet in the past has resulted in sea level rise.
- Warming has decreased sea ice, which in turn strongly magnifies warming, and seasonally ice-free conditions and even year-round ice-free conditions have occurred in response to sufficiently large but poorly quantified forcing.
- Although major climate changes have typically affected the whole Arctic, important regional differences have been common; a full understanding of Arctic climatology and paleoclimatology requires regionally-resolved studies.

References Cited

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