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Past Climate Variability and Change in the Arctic and at High Latitudes

Chapter 1 — Executive Summary

Chapter Lead Authors

Richard B. Alley, Pennsylvania State University, University Park, PA

Julie Brigham-Grette, University of Massachusetts, Amherst , MA

Gifford H. Miller, University of Colorado, Boulder, CO

Leonid Polyak, Ohio State University, Columbus, OH

James W.C. White, University of Colorado, Boulder, CO

1.1 **Introduction**

Paleoclimate records play a key role in our understanding of Earth's past and present climate system and in our confidence in predicting future climate changes. Paleoclimate data help to elucidate past and present active mechanisms of climate change by placing the short instrumental record into a longer term context and by permitting **models** to be tested beyond the limited time that instrumental measurements have been available.

Recent observations in the Arctic have identified large ongoing changes and important **climate feedback mechanisms** that multiply the effects of global-scale climate changes. Ice is especially important in these "Arctic amplification" processes, which also involve the ocean, the atmosphere, and the land surface (vegetation, soils, and water). As discussed in this report, paleoclimate data show that land and sea ice have grown with cooling temperatures and have shrunk with warming ones, amplifying temperature changes while causing and responding to ecosystem shifts and sea-level changes.

1.2 Major Questions and Related Findings

How have temperature and precipitation changed in the Arctic in the past? What does this tell us about Arctic climate that can inform projections of future changes?

The Arctic has undergone dramatic changes in temperature and precipitation during the past 65 million years (m.y.) (the Cenozoic Era) of Earth history. Arctic temperature changes during this time exceeded global average temperature changes during both warm times and cold times, supporting the concept of Arctic amplification.

At the beginning of the Cenozoic Era, 65 million years ago (**Ma**), there was no sea ice on the Arctic Ocean, and neither Greenland nor Antarctica supported an ice sheet. General cooling since that time is attributed mainly to a slow decrease in **greenhouse gases**, especially carbon dioxide, in the atmosphere. Ice developed during this slow, "bumpy" cooling, first as mountain glaciers and as seasonal sea ice with the first continental ice sheet forming over Antarctica as early as 33 Ma ago. Following a global warm period about 3.5 Ma in the middle Pliocene, when extensive deciduous forests grew in Arctic regions now occupied by **tundra**, further cooling crossed a threshold about 2.6 Ma, allowing extensive ice to develop on Arctic land areas and thus initiating the Quaternary ice ages. This ice has responded to persistent features of Earth's orbit over tens of thousands of years, growing when sunshine shifted away from the Northern Hemisphere and melting when northern sunshine returned. These changes were amplified by feedbacks such as **greenhouse-gas** concentrations that rose and fell as the ice shrank and grew, and by the greater reflection of sunshine caused by more-extensive ice. Human civilization has developed during the most recent of the relatively warm **interglacials**, the Holocene (about 11.5 thousand years ago (**ka**) to the present). The penultimate warm interval, about130–120 ka, received somewhat more Northern-Hemisphere summer sunshine than the Holocene owing to differences in Earth's orbital configuration. Because this more abundant summer sunshine warmed the Arctic summer about 5°C above recent temperatures, the Greenland Ice Sheet was substantially smaller than its current size and almost all glaciers melted completely at that time.

The last glacial maximum peaked at about 20 ka when the Arctic was about 20°C colder than at present. Ice recession was well underway by 16 ka, and most of the Northern Hemisphere ice sheets melted by 7 ka. Summer sunshine rose steadily from 20 ka to a maximum (10% higher than at present due to the Earth's orbit) about 11 ka ago, and has been decreasing since then. The extra energy received in summer in the early Holocene resulted in warmer summers throughout the Arctic. Summer temperatures were 1°–3°C above 20th century averages, enough to completely melt many small glaciers in the Arctic and to slightly shrink the ice sheet on Greenland. Summer sea-ice limits were significantly less than their 20th century average. As summer sunshine decreased in the second half of the Holocene, glaciers re-established or advanced, and sea ice became more extensive. Late Holocene cooling reached its nadir during the Little Ice Age (about 1250–1850 AD), when most Arctic glaciers reached their maximum Holocene extent. The Little Ice Age temperature minimum may also have been augmented by multiple large volcanic eruptions that lofted a reflective aerosol layer into the stratosphere at that time. Subsequent warming during the 19^{th} and 20^{th} centuries has resulted in Arctic-wide glacier recession, the northward advance of terrestrial ecosystems, and the reduction of perennial (year-round) sea ice in the Arctic Ocean. These trends will continue if greenhouse gas concentrations continue to increase into the future.

Paleoclimate reconstructions of Arctic temperatures compared with global temperature changes during four key intervals during the past 4 m.y. allow a quantitative estimate of Arctic amplification. These data suggest that Arctic temperature change is 3 to 4 times the global average temperature change during both cold and warm departures.

***How rapidly have temperature and precipitation changed in the Arctic in the past? What do these past rates of change tell us about Arctic climate that can inform projections of future changes*?**

As discussed with the previous question, climate changes on numerous time scales for various reasons, and it has always done so. In general, longer-lived changes are somewhat larger but much slower than shorter- lived changes.

Processes linked to **continental drift** (**plate tectonics**) have affected atmospheric and oceanic currents and the composition of the atmosphere over tens of millions of years; in the Arctic, a global cooling trend has switched conditions from being ice-free year-round near sea level to icy conditions more recently. Within the icy times, variations in Arctic sunshine in response to features of Earth's orbit have caused regular cycles of warming and cooling over tens of thousands of years that were roughly half the size of the continental-drift-linked changes. This "glacial-interglacial" cycling was amplified by colder times bringing reduced greenhouse gases and greater reflection of sunlight, especially from expanded ice-covered regions. This glacial-interglacial cycling has been punctuated by sharp-onset, sharp-end (in as little as 1–10 years) **millennial oscillations**, which near the North Atlantic were roughly half as large as the glacial-interglacial cycling but which were much smaller Arctic-wide and beyond. The current warm period of the glacial-interglacial cycling has been influenced by cooling events from single volcanic eruptions, slower but longer lasting changes from random fluctuations in frequency of volcanic eruptions and from weak solar variability, and perhaps by other classes of events. Very recently, human effects have become evident, not yet showing both size and duration that exceed peak values of natural fluctuations further in the past, but with projections indicating that human influences could become anomalous in size and duration and, hence, in speed.

***What does the paleoclimate record tell us about the past size of the Greenland Ice Sheet and its implications for sea level changes*?**

The paleo-record shows that the *Greenland Ice Sheet* has consistently lost mass and contributed to sea-level rise when the climate warmed, and has grown and contributed to sea-level fall when the climate cooled. This occurred even at times when offsetting effects from elsewhere in the climate system caused the net sea-level change around Greenland to be negligible, and so these changes in the ice sheet cannot have been caused primarily by sea-level change. In contrast, no changes in the ice sheet have been documented independent of temperature changes. Moreover, snowfall has increased with major climate warmings, but the ice sheet lost mass nonetheless; increased accumulation in the ice sheet center was not sufficient to counteract increased melt and flow near the edges. Most of the documented changes (of both ice sheet and **forcings**) spanned multi-millennial periods, but limited data show rapid responses to rapid forcings have also occurred. In particular, regions near the ice margin have been observed to respond within a few decades or less. However, major changes of the ice sheet are thought to take centuries to millennia, and this is supported by the limited data.

The paleo-record does not yet give any strong constraints on how rapidly a near-complete loss of the ice sheet could occur, although the paleo-data indicate that onset of shrinkage will be essentially immediate after forcings begin. The available evidence suggests such a loss requires a sustained warming of at least 2-7^{o}C above mean 20th century values, but this threshold is poorly defined. The paleo-archives are sufficiently sketchy that temporary ice sheet growth in response to warming, or changes induced by factors other than temperature, could have occurred without being recorded.

What does the paleoclimate record tell us about past changes in Arctic sea ice cover, and what implications does this have for consideration of recent and potential future changes?

Although incomplete, existing data outline the development of Arctic sea-ice cover from the ice-free conditions of the early Cenozoic. Some data indicate that sea ice has covered at least part of the Arctic Ocean for the last 13–14 million years, and it has been most extensive during the last several million years in relationship with Earth's overall cooler climate. Other data argue against the development of perennial (year-round) sea ice until the most recent 2 – 3 million years. Nevertheless, episodes of considerably reduced ice cover, or even a seasonally ice-free Arctic Ocean, probably punctuated even this latter period. Warmer climates associated with the **orbitally-paced** interglacials promoted these episodes of diminished ice. Ice cover in the Arctic began to diminish in the late 19th century and this shrinkage has accelerated during the last several decades. Shrinkages that were both similarly large and rapid have not been documented over at least the last few thousand years, although the paleoclimatic record is sufficiently sparse that similar events might have been missed. Orbital changes have made ice melting less likely than during the previous millennia since the end of the last ice age, making the recent changes especially anomalous. Improved reconstructions of sea-ice history would help clarify just how anomalous these recent changes are.

1.3 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, including the CAPE Project, and multiply replicated, 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 are quite valuable and will become more so with synthesis and replication, including comparison with land-based and 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 paleoclimatic change. ***Future research should 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 many 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. ***Future research activities in Arctic paleoclimate should address in greater detail the policy-relevant questions motivating 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 in soils is 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 ice will melt and associated impacts will follow, with implications for ecosystems and economies. ***The results presented here should be utilized by science managers in the design of monitoring, process, and model-projection studies of Arctic change and linked global responses.***