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OPINION

Polar paleoenvironmental perspectives on modern climate change

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Earth's polar regions are at the forefront of environmental and climatic change. One clear example is the accelerating loss of Arctic summer sea ice due to polar amplification from 1979 to 2021 [1]. Declining sea ice is leading to unprecedented marine ecosystem changes [2], creating complex ecological consequences on food webs and biodiversity. Warmer and fresher ocean advection from subarctic Pacific and North Atlantic waters into the Arctic Ocean are supporting boreal species farther north, a process termed borealization [3]. To prepare for future climate conditions, resource and policy managers need information about changes that could occur. The geological record–lithological, physical, biological, and chemical archives of climate history–combined with the geomorphological and ice-core records (Fig 1) provide evidence for how ocean, atmosphere and biological systems have responded to past climate changes. We highlight four key research topics where paleoclimate data can improve our understanding of past, present, and future drivers of environmental change.

1. Ice sheet sensitivity and global sea level

Paleoclimate proxy records in marine and terrestrial sediment cores and ice cores from polar regions have established that atmospheric CO_2 is both a driver and feedback for Quaternary glacial-interglacial climate change, which follows cyclical changes in the Earth's orbit. During interglacial periods, greater high-latitude insolation and greenhouse gas levels led to ice sheet melting and sea-level changes of tens to hundreds of meters. Based on direct measurements from air trapped in Antarctic ice, we know that present-day CO_2 levels are higher now than in the past 800,000 years [2]. Modern observations can not tell us how sensitive ice sheets and their various outlet glaciers and ice shelves are to atmospheric and ocean warming, or how much sea level will rise due to continued anthropogenic greenhouse gas emissions.

One way to better understand ice sheet response to climate is to study past intervals when interglacial climate conditions were similar to or warmer than today, such as ~125,000 (the Eemian) and ~400,000 years ago. Multiple lines of evidence indicate a massive retreat of the Greenland Ice Sheet (and possibly the West Antarctic Ice Sheet) ~400,000 years ago gave way to ice-free conditions and boreal forests on Greenland [4] and global sea level 6–13 meters higher than today [5]. Proxy data corroborating this higher-than-present sea level and warm climate include shoreline features [5], pollen [4], microfossil assemblages, stable isotope and Mg/Ca ratios [6], leaf-wax biomarkers [7], and ice-core records [8], among others. About 400,000 years ago, CO_2 concentrations were ~280 parts per million (ppm) compared to 420 ppm today, but the average global air temperature was similar to what Earth may experience in the near future [2]. To better anticipate future impacts, models can be supplemented with more paleorecords of ice volume, sea level, atmospheric and ocean temperatures and ice-

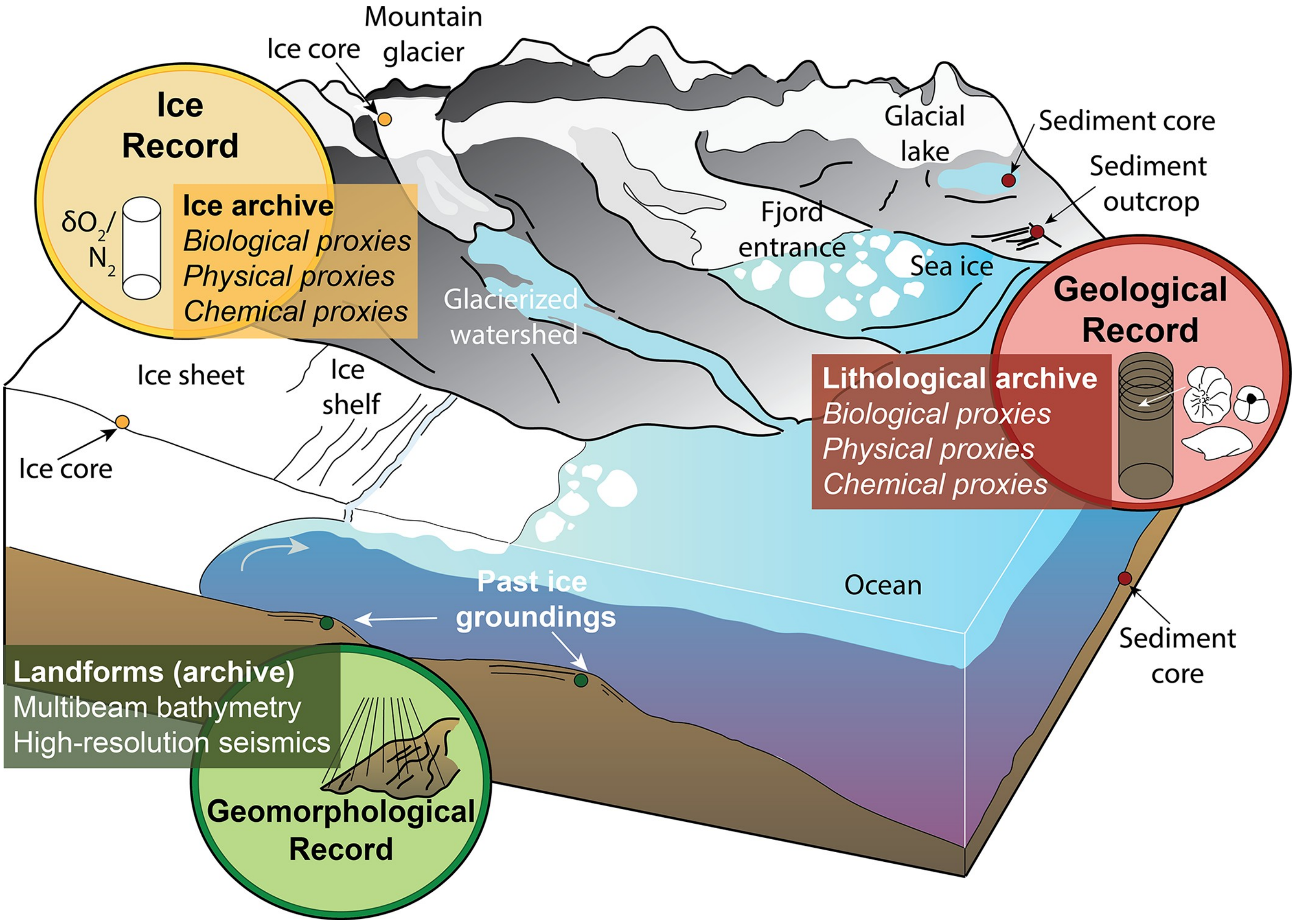

Fig 1. Diagram of glacial environments showing the types of records/proxies used to reconstruct past climates and environments.

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sheet history to help clarify mechanisms and sensitivities of the climate system during interglacial periods.

2. Marine ecosystem impacts

Paleoenvironmental perspectives can shed light on other pressing questions, such as oceanographic and ecosystem impacts on the polar regions during the most recent time the Eurasian Arctic Ocean was seasonally sea-ice free. This is especially important given that an expansion of (relatively) warm Atlantic waters into the Arctic Ocean is currently being documented, accelerating sea ice loss and borealization of the Barents Sea ecosystem [9]. Proxies in sediment cores well-dated to the Eemian (~125,000 years ago) find that subpolar planktic species associated with Atlantic water expanded deep into the Arctic Ocean [10]. Likewise, proxy records of sea ice distribution based upon biomarkers from primary producers support that strong Atlantic water inflow created open-water conditions in the Eurasian Basin [11]. Obtaining cores with higher rates of sedimentation from the Arctic Ocean can help improve understanding of climate and ocean variability during past warm periods, and how Atlantic inflows affect sea ice and ecosystem dynamics. An example of this is an 800-year high-resolution reconstruction using organic biomarkers and benthic foraminifera that showed a 20th century increase in borealization along Greenland and Svalbard compared to earlier centuries [12].

3. Global ocean circulation

During the last glacial interval (80,000 to 11,000 years ago), numerous sudden changes from ice sheet melt caused variations in the strength of the Atlantic Meridional Overturning Circulation (AMOC), a major branch of the global ocean conveyer belt that redistributes heat, salt, and nutrients. Rapid atmospheric warming events (up to 15˚C) over a few decades are recorded by multiple proxies in North Atlantic marine sediments (foraminifera, molluscs), in speleothems and corals, and in Greenland ice cores [2]. This sudden warming demonstrates that abrupt changes in climate and ocean circulation occurred in the past and can potentially happen in the future. Presently, with the continued melting of the Greenland Ice Sheet and freshwater inputs from other sources into the North Atlantic, the strength of the AMOC may already be in a slowed state [13], and future disruptions are predicted with continued anthropogenic forcing [14]. This circulation system has been identified as a key tipping point of the Earth's climate system [2]. Paleoclimate study, such as quantifying past changes in AMOC variability, is an important area of research because ocean circulation changes can cause significant impacts on sea-level, weather patterns, and coastal ecosystems affecting agricultural and fisheries productivity.

4. Climate model-paleo data comparisons

A significant component of climate science is computer modelling aimed at a better understanding of future climate change scenarios that can be used to inform policies and decision-making. Proxy records from polar regions are increasingly used in paleoclimate modeling to build paleoenvironmental reconstructions used to initiate model experiments and to verify model results [2]. To improve our understanding further, the '*Paleoclimate Modelling Intercomparison Project'* compares simulations of past climates across different models and against paleo-observations. These efforts can lead to an increased understanding of the strengths and weaknesses of different models and ultimately builds confidence in those models used to project future climate conditions. However, recent warming and reductions in ice sheets, alpine glaciers and sea ice cover in both polar regions have been generally underestimated by models [15]. A focus on improving proxy data coverage and developing more semi-quantitative proxy records of Quaternary sea ice and climate conditions in polar regions for model input can help resolve how slow-responding components of the climate system operate over centuries to millennia.

In conclusion, polar paleoenvironmental perspectives are critical to understand climate dynamics and to plan for our future world. The profound and rapid transformations being observed in Arctic and Southern Ocean ecosystems–and the further changes expected over the next few decades–emphasize the importance of understanding climate and ecosystem mechanisms/processes from a long-term perspective. Polar paleorecords provide critical data that proxies from non-polar regions do not, such as (1) how sensitive ice sheets are to melting and sea-level change, (2) how high latitude/high productivity ecosystems are affected under warmer scenarios, (3) how AMOC strength affects ocean heat transport, and (4) to validate poorly constrained high-latitude model boundary conditions. Although the past does not provide an exact analog for the coming centuries, multiproxy paleodata and models are important and reliable sources to predict and prepare for the future.

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