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Hotspots in the Arctic: Natural archives as an early warning system for global warming

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Hotspots in the Arctic: Natural archives as an early warning system for global warming

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The summer of 2012 has seen another dramatic new minimum of sea-ice coverage in the Arctic Ocean, reaching a value that was predicted by the most pessimistic models in the report of the Intergovernmental Panel for Climate Change (http://www.ipcc.ch) only for as late as 2030–2040 (Meehl and Stocker, 2007; Stroeve et al., 2007). Other time series of Arctic environmental parameters, like snow coverage and air temperatures, also show clear signs of a warming that is faster than in any other area of comparable size on Earth. Is this Arctic warming already beyond the range of natural variability? Although there is no simple answer to this question, scientists are now developing new approaches to compare the modern environment in the Arctic to conditions in the past. Boundary conditions like, e.g., land-sea configurations, large-scale oceanic circulation patterns, and insolation have varied considerably over geologic time, often making comparisons to the "distant" geological past meaningless in this context. Instead, researchers are now in search of and analysing relatively "young" Arctic paleotemperature time series, preferentially from the (Late) Holocene when comparisons may be made with more confidence. Historical climate observations and precise temperature measurements in the Arctic rarely reach back into the 19th century, and thus do not contain data from the pre-industrial era. The lack of trees in most parts of the high Arctic largely precludes the use of dendrological data for reconstructions. Therefore, most of the suitable continuous Holocene climate records come from ice caps, lakes, and the ocean. Each of these archives has its own assets and drawbacks in the Arctic. Ice cores can resolve a (sub)annual variability, but records from the top of the huge Greenland ice sheet display a temperature range significantly different from what is found near sea level. Smaller ice sheets from lower elevations, however, can be subject to surface melting and meltwater percolation, in particular during warmer periods. Marine sediment cores may contain continuous records, but low sediment fluxes in cold waters and bioturbation from bottom-dwelling animals often render the establishment of high-resolution paleotemperature records difficult. Sediment cores from Arctic lakes that receive sufficient sediment supply are left as potential candidates for the paleoclimate records needed to answer our question.

This issue of *Geology* presents two examples of such records from an area that plays a particularly important role for heat transfer to the Arctic. The Fram Strait between Svalbard and North Greenland is the major connection between the Arctic Ocean and the North Atlantic. Relatively warm, saline Atlantic waters enter the Arctic Ocean in the east of this passage, while cold, low-saline waters and sea ice are exported southward in the west, maintaining a strong east-west temperature contrast throughout the year. Perren et al. (p. 1003 in this issue) report on the reawakening of world's northernmost lake, situated close to the Arctic Ocean shore on North Greenland (83°37′N). According to their results from a sediment core, this lake has been almost completely abiotic for more than 2000 yr, except for some cyanobacterial activity. Early in the 20th century, however, algae returned to the lake and have now established a relatively diverse community that is as rich or richer than 2400 yr before, when algae became extinct there. A nitrogen isotope record of the core demonstrates that "fertilization" by long-range atmospheric transport of anthropogenic nitrogen is an unlikely cause for the revival of algae in this remote place in the Arctic. Accordingly, Perren et al. conclude that the lake had been completely frozen over for more than two millennia, and that an air temperature increase since ca. A.D. 1920 has thawed the ice in the short summers so that photosynthetic algae could bloom. This result, and its timing, are in line with a number of other observations from the Arctic. The A.D. 1920–1940 interval saw an air temperature increase throughout the Arctic comparable to what was measured in the last two decades (Chylek et al., 2009), a significant decrease of sea ice in the Greenland Sea (Vinje, 2001), and the onset of the ongoing dramatic sea-ice loss in the Arctic Ocean after more than 1300 yr of minor variability (Kinnard et al., 2011). All of these developments have made additional heat available to northern Greenland, so that even the world's northernmost lake has awakened after more than 2000 yr of hibernation.

Further alarming evidence comes from the eastern side of Fram Strait. D'Andrea et al. (p. 1007 in this issue) present a record of summer air temperatures for western Svalbard that reaches back 1800 yr and is of unprecedented temporal resolution. This study is pioneering in various ways, and may open new possibilities for high-resolution paleoclimate research in this area. The authors were the first to successfully establish an age model based on tephrochronology for the pre-industrial part of a Holocene lake record from Svalbard. Earlier attempts to do so had yielded unsatisfactory results due to problems with the very low number of tephra grains in lake sediments, which were difficult to assign to specific eruptions. Second, D'Andrea and his colleagues were able to reconstruct paleotemperatures from the analysis of alkenones, which are organic substances produced by, e.g., algae. They calibrated analytical results from sediments of the past 100 yr to a local instrumental temperature record and found that average summer temperatures were highly variable over the past 1800 yr. Highest air temperatures occurred in the past ~100 yr, similar to what was found for Atlantic Water temperatures off western Svalbard (Spielhagen et al., 2011), suggesting a strong link of warming in the nearby ocean and on Svalbard. Somewhat unexpected, however, is the reconstruction of increasing summer temperatures on western Svalbard in the 18th and 19th centuries, the younger part of the so-called Little Ice Age (LIA) and a period of sustained cool climate in Europe (e.g., Luterbacher et al., 2004). This warming, in particular, seems at odds with the well-known late-LIA glacier advance on Svalbard (Werner, 1993). D'Andrea et al. suggest that increased wintertime precipitation may have been the major control for LIA glacier growth, instead of low summer temperatures. Recent results from other climate archives in the area are in support of this hypothesis. Oxygen isotope data from ice cores drilled in western and central Svalbard ice caps point to low winter temperatures in the LIA (Divine et al., 2011). Furthermore, a study of sea-ice indicative biomarkers and ice-rafted debris in a Holocene sediment core from the western Svalbard continental margin (Müller et al., 2012) suggests that a warmer ocean with reduced sea-ice cover off Svalbard intensifies evaporation, which might eventually lead to increased precipitation and glacier growth on Svalbard. Interestingly, the ocean temperature record from the same site reveals a warming of Atlantic Water that had already started in the 18th century (Spielhagen et al., 2011), contemporary to the onset of warming on western Svalbard, as seen in the new Svalbard lake record.

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The results from the various marine and terrestrial archives and proxies in the Svalbard area reveal a complex relationship of oceanic and terrestrial environments that may apply to various areas in the Arctic under conditions of past, present, and future warming. Ocean warming enhances evaporation, leading to higher precipitation on nearby land, and potentially to glacier growth. Above a certain temperature threshold, however, higher preciptation and glacier melting will result in more freshwater runoff, which reinforces oceanic stratification through formation of a low-salinity surface layer, as it is found today in the central Arctic and the western Fram Strait. With increasing runoff, the buoyancy of this layer causes a regional expansion, a shielding of the underlying warmer water from the atmosphere, and a reduction of ocean-to-land heat fluxes in the area. Microfossil data do, indeed, point to a surface-water cooling and southeastward expansion of the sea ice cover off northwest Svalbard in the past 300 yr (Bonnet et al., 2010), and may explain the cool LIA winters as reconstructed from the ice cores (Divine et al., 2011). However, some of the results still seem contradictory, and underscore the need for more high-resolution paleoclimate records from the Arctic, which will help us to better understand the internal climate feedbacks in the Arctic system.

Altogether, the lake records from North Greenland and Svalbard presented in this issue of *Geology* add two further hotspots to the Arctic heat map. Considering also the Atlantic Water record from the Fram Strait (Spielhagen et al., 2011), they convincingly show that modern conditions in the area are unprecedented for the past ~2000 yr or more, and the result of a sustained warming in the past ~100 yr. To answer our initial question, they indeed suggest that the climate system has left the range of natural climate variability in this time frame. To estimate where the Arctic environment is heading under further warming, records from natural archives of past warm periods with less sea ice are needed. A potential candidate is the Holocene Thermal Maximum (HTM) which was time-transgressive around the Arctic (Renssen et al., 2009) but largely related to the insolation maximum in high latitudes at 9–10 kyr B.P. This period is of special interest because maximum northward heat advection from the Atlantic at ca. 10 kyr B.P. (Risebrobakken et al., 2011), followed by minimum sea ice in the eastern Fram Strait at ca. 8 kyr B.P. (Müller et al., 2012), allow speculations on a strongly diminished sea-ice cover also in the interior Arctic. Unfortunately, no high-resolution records exist so far from the deep-sea Arctic Ocean to support this hypothesis. The same accounts for the last interglacial period (ca. 130–115 kyr B.P.), another potential analog for future conditions. There is ample evidence from lower latitudes for warmer climates, and results of numerical modeling based on circum-Arctic terrestrial data suggest less sea ice than today (Otto-Bliesner et al., 2006). Again, however, no continuous records of sufficient resolution from the interior Arctic are there to support this scenario. While the present response of the Arctic to global warming must be regarded as unequaled with regard to the younger geological history (the past several thousand years), there is an urgent need for further research on potential past analogs of the Arctic of tomorrow.

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