Glacial demise and methane's rise

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The historical sciences—geology, archeology, and cosmology—test hypotheses differently than the experimental, laboratory sciences. When the process or event being investigated took place long ago or at a great distance from the investigators, hypotheses are tested by assembling key data that can support or refute the likelihood of the proposed explanation. In this way, we have developed understanding and agreement on many major events in Earth history, such as the Cretaceous–Tertiary extinction or the glacial–interglacial cycles of the Pleistocene epoch. A consilience of findings is required, and in a mechanistic, causative model, timing is of critical importance. If a key factor in the explanation can be shown to have occurred at a time inconsistent with the model—too early or too late—the hypothesis has to be modified or rejected. In PNAS, Reyes and Cooke (1) apply a refined dating approach to assess the timing of deglacial environmental change across the high-latitude circumpolar Arctic and its relation to increases in a major atmospheric greenhouse gas, methane. In their study, these investigators use improved methods for presentation and interpretation of the initiation dates for a very large dataset of Arctic peatland, tundra, and thermokarst sites to demonstrate that their development occurred too late to be the principal cause of impressively abrupt and large methane increases in atmospheric methane abundance at the beginning of the Bølling and the end of the Younger Dryas climatic intervals of the last deglaciation (2).

Late Quaternary sediments younger than approximately 50,000 y in age are chiefly dated by ^{14}C decay. Because of variations in stratospheric production rates and changes in the size of oceanic reservoirs, the amount of ^{14}C originally incorporated in biogenic material has not been constant over time (3). Additionally, statistical uncertainty is larger in older ^{14}C counting measurements than in those obtained by accelerator mass spectrometry—the modern gold standard for radiocarbon dating. Consequently, instead of a single date, ^{14}C dating techniques produce an irregular, non-Gaussian probability distribution of estimated ages for every analyzed sample. Previous studies of peatland initiation and rates of carbon accumulation that integrated large datasets represented the uncertainty of each date as a simple age range, with equal probability of occurrence in each binned time interval of the entire time span (e.g., ref. 4). For dating initial peat deposits, the standard method of presentation spreads the apparent age distribution and,

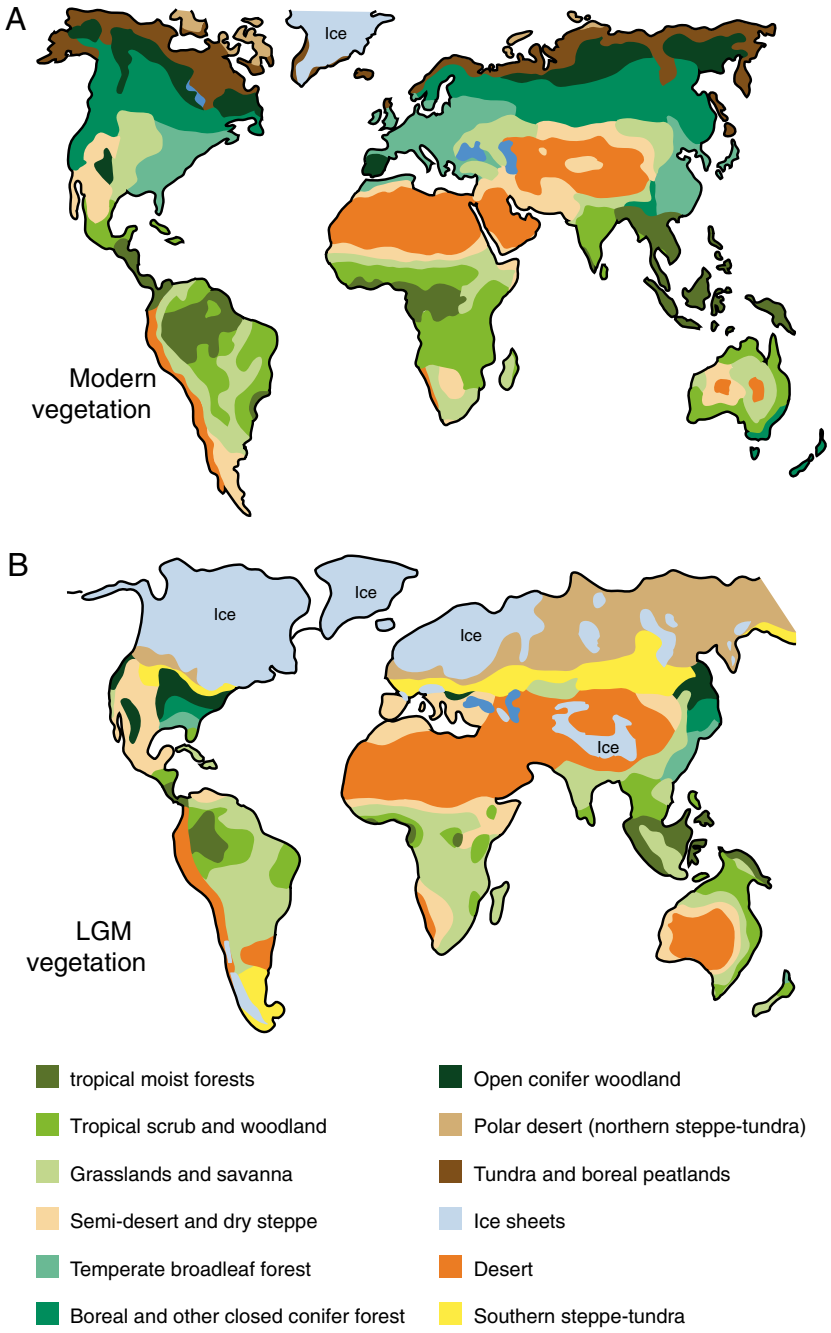

Fig. 1. Comparison of the distribution of vegetation types and ice sheet extent between (*A*) modern and (*B*) Last Glacial Maximum (LGM) (13, 14). The LGM was marked by much wider distribution of dry vegetation biotopes, including those of deserts, grasslands and savanna, semidesert and dry steppe, polar desert, and southern steppe tundra compared with the present day. [Reproduced with permission from ref. 14 (Copyright 2003, American Geophysical Union).]

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in particular, skews the estimated age of events and transitions to older ages and decreases the ostensible rates of change. The more sophisticated application of summed age probability distributions by Reyes and Cooke (1) improves our understanding of the relationship between environmental change, boreal peatland development, carbon accumulation, and production of atmospheric methane by sharpening and refining aspects of timing and sequence.

Methane is possibly the most intriguing and least understood of the naturally occurring atmospheric greenhouse gases. It shows far greater sensitivity and covariance with climate change than carbon dioxide (5), especially with the rapid and transient transitions discovered from the last climatic cycle. It also has been hypothesized to be the earliest significant anthropogenic greenhouse gas to have increased in atmospheric concentration (6). The most broadly held explanation for methane's covariation with climate is that its atmospheric concentration is a largely passive, if rapid, response to climate change, following widespread increases in temperature, precipitation, and melting of vast areas of the Earth's surface that were frozen or covered by continental ice sheets (7, 8).

Although generally two orders of magnitude less abundant than carbon dioxide, methane is a powerful greenhouse gas, with 25 times the greenhouse warming potential (GWP) of CO_2 on the 100-y time frame and an amazing 62 times the GWP on a shorter 20-y time scale (9). Its production has long been linked to generation by anaerobic methanogenic bacteria in saturated soils, namely in wetlands, peatlands, moist forests, and mires (10), and climatically driven expansion of such wetlands is the generally accepted explanation for a doubling in postglacial atmospheric methane concentration. Hemispheric differences in atmospheric methane recorded by ice cores indicate that the northern hemisphere would have been the primary source of most past increases (8, 11). However, explanation of the atmospheric methane record is not as simple as simply switching on northern hemisphere peatlands at the end of the last ice age (12).

In conjunction with global warming and the demise of the large high-latitude continental ice sheets, striking environmental changes occurred at all latitudes from the tropics to the Arctic (Fig. 1), both on land and in the ocean (13). These changes—primarily related to increased temperature and precipitation, but also including migration of meteorologic boundaries—encompassed many physical, biological, and climatic shifts that could modulate processes related to methane fluxes to and from the atmosphere (14). Although many potential sources or sinks of methane have been modeled or investigated, the body of evidence does not unequivocally support any one cause for the entire glacial-to-Holocene behavior of the atmospheric methane record. Among the potential drivers of all or part of the deglacial methane increase are these: thawing of organic-rich tundra and development of thermokarst lakes (15); emissions of thermogenic methane from hydrocarbon reservoirs (16); destabilization of methane hydrates and the release of trapped gas associated with the vast marine deposits (14, 17); direct methane production by plants (18); increased uptake by invigorated methanotrophic microbial communities in soils (19); biomass burning (20); and decreased atmospheric oxidation of methane catalyzed by plant-produced volatile organic compounds produced by an expanding terrestrial biomass (21).

Isotopic analyses of ice and argon in Greenland ice cores indicate that atmospheric methane increased nearly simultaneously (within 0–100 y) with temperature increases over Greenland during the last deglaciation (22, 23). Reyes and Cooke's study (1), however, demonstrates that major increases in the rates of initiation of circum-Arctic and Alaskan peatlands and Canadian thermokarst lakes lagged increases in atmospheric methane at 14.7 and 11.6 ka by 500 to >1,000 y. Because the methane record so closely mimics the isotopic climate record for the northern hemisphere, other climatically sensitive sources or sinks must have been poised to rapidly switch on with deglaciation—but which ones?

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