PERSPECTIVES: CLIMATE RECONSTRUCTION

The Value of Multiple Proxies

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Reconstructions of Northern Hemisphere (NH) temperatures in past centuries provide evidence that the warming of the late 20th century is unprecedented in at least the past millennium (*1–4*). But how are these reconstructions obtained? And how reliable are they?

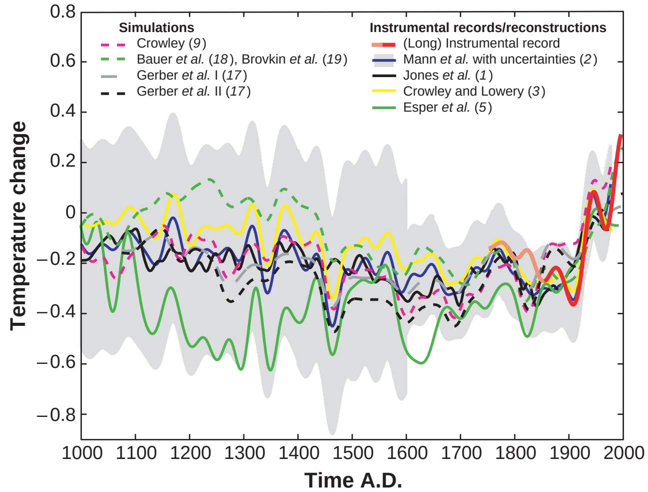
Widespread, direct instrumental measurements of surface temperature are available only for the past hundred years or so. Indirect or "proxy" indicators of climate variability must therefore be used to reconstruct earlier changes. To ensure their reliability, reconstructions based on these proxies must be validated by comparison with instrumental records during periods of overlap.

Climate proxies such as pollen, ocean-sediment cores, lake-level reconstructions, glacial moraines, and terrestrial and ice-borehole data provide valuable insights into broad patterns of climate variability on longer time scales. However, with the exception of some ocean-sediment cores, their resolution is too coarse to allow validation against instrumental data. Attempts to reconstruct climate patterns over the past few centuries have therefore used annually resolved proxies such as tree rings, corals, ice cores, lake sediments, and the few available multicentury historical and instrumental series (*4*).

Unfortunately, no one proxy alone is adequate for reconstructing large-scale patterns of past climate. Tree-ring data are the most widespread source of annual proxy climate information, but have several limitations. First, they only provide information on subpolar terrestrial regions, and thus far, generally only extratropical species have proven useful for climate reconstruction.

Second, it remains a subject of debate how best to estimate climate variability on multicentennial time scales from tree-ring data (*5–7*). The accuracy of long-term estimates based solely on tree-ring data is therefore hard to assess.

Third, tree-ring data from most regions reflect warm-season conditions, with cold-season information limited to species from semiarid and Mediterranean environments. This seasonal specificity may give a misleading view of large-scale temperature changes, because the climate response to volcanic forcing, for example, leads to opposite temperature changes in summer (cooling) and winter (warming) over the continents (*8*). Volcanic forcing was probably the dominant source of variation in radiative forcing prior to anthropogenic influences (*9*). Tree-ring reconstructions of warm-season extratropical continental temperature changes thus provide valuable measures of past volcanic forcing (*10*) but are not indicative of annual mean changes across the full hemisphere.



NH temperature histories. Comparison of multiproxy reconstructions of the NH annual mean temperature (*1–3*) with model simulations (*9*, *17–19*). Gerber I, 1.5°C for CO_2 doubling; Gerber II, 2.5°C for CO_2 doubling. Also shown is a reconstruction of summer extratropical continental NH temperatures (*5*). All reconstructions have been scaled to the NH instrumental record (*20*) over the 1856 to 1980 period, and have been smoothed on time scales of >40 years to highlight the long-term variations.

Coral information (such as oxygen isotopes and chemical species ratios that respond to temperature and salinity changes near the ocean surface) offer information regarding tropical and subtropical climate changes, represent maritime regions, and continuously sample their environment over the full year. However, long (multicentury) records are rare, and the possible influence of nonclimatic influences has not yet been confidently established.

Ice cores typically provide information from polar regions and high-elevation tropical and extratropical environments. They are spatially complementary to tree rings and corals, but sample a very small part of the global surface. An indisputable interpretation of ice-core oxygen isotopes in terms of atmospheric temperature variability, moreover, remains elusive, and precise annual dating can be difficult.

Finally, long historical documentary climate records, arguably the most reliable "proxy" information of all, are restricted to a few locations in Europe and east Asia.

"Multiproxy" methods exploit the complementary strengths of each of these proxies to reconstruct large-scale climate changes in past centuries. In this way, climate indices such as the North Atlantic Oscillation (NAO) index (*11*), large-scale temperature (*12*) and sea level pressure (*13*) patterns, and hemispheric mean temperature (*2–4*) have been reconstructed.

Several methods have been used to assimilate the multiproxy data into a climate reconstruction. The simplest methods average over a set of standardized proxy series believed to track a particular quantity (such as surface temperature). The resulting hemispheric or global composite is then scaled against an appropriate target index (such as the instrumental hemispheric temperature series) to yield a reconstruction of that index (*1*, *3*).

A more elaborate method uses a multivariate calibration of the proxy data against the instrumental record (*12–14*). An estimate of hemispheric mean temperature can, for example, be derived by averaging over the reconstructed surface temperature patterns (*12*). Information regarding the underlying spatial pattern is, however, retained. This approach thus provides a distinct advantage over simpler approaches, for example, when information on the spatial response to forcing is sought (*15*).

No a priori local relation between proxy indicator and climatic variable (such as temperature) is assumed in the multivariate approach. Instead, the large-scale field is simultaneously calibrated against the full information in the network. The calibrated relation is determined from the 20th-century period, during which anthropogenic forcing played a prominent role. The approach could therefore yield a biased reconstruction of the past if the fundamental patterns of past temperature variation differ from those recorded in modern surface temperatures. However, tests with forced and control model simulations indicate that the methodology is insensitive to this problem given an adequate (~100-year) calibration period (*16*).

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Coupled with model simulation results, multiproxy reconstructions can elucidate the roles of natural and anthropogenic forcing in past climate change and inform our assessment of likely future changes. Simulations using a moderate sensitivity to radiative forcing (1.5° to 2.5°C for CO_2 doubling) (*9*, *17–19*) show a close overall agreement with multiproxy temperature reconstructions (see the figure). One of these simulations, which incorporates an interactive carbon cycle model, has been shown to reproduce observed preanthropogenic natural variations in CO_2 concentration (*17*), providing an independent verification of the model's sensitivity and temperature history. Simulations incorporating the effects of human land-use changes (*18*, *19*) provide the best agreement with reconstructions and instrumental data during the 19th and 20th centuries.

A NH extratropical, continental summer temperature tree-ring reconstruction (*5*) exhibits significantly greater cooling at various times than is evident in any multiproxy or model estimates (see the line in the figure). This discrepancy probably arises, at least in part, from enhanced extratropical continental responses to forcing, including the enhanced summer continental cooling signature of volcanic forcing.

The spatial and temporal details of climate changes during the past millennium should become increasingly better resolved through expanded and improved networks of multiproxy data. It should therefore soon be possible to use high-resolution reconstructions of the past 500 to 1000 years or so as a template for calibrating networks of longer-term, lower-resolution proxy data. This possibility holds prospects for reconstructing the spatial details of climate changes over several millennia, potentially resolving key details regarding the climate changes of the entire postglacial period of the past 10,000 years.

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PERSPECTIVES: ECOLOGY

Fall and Rise of the Black Sea Ecosystem

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During the 1980s and early 1990s, the Black Sea ecosystem was in a catastrophic condition [for reviews see (*1–4*)]. The deterioration of this ecosystem was the result of two principal factors: eutrophication (that is, nutrient enrichment due to domestic or agricultural waste) and invasion by the comb jelly *Mnemiopsis* (see the figure, bottom). These factors were exacerbated by pollution and overfishing. Remarkably, since the mid-1990s, the impact of both eutrophication and *Mnemiopsis* has declined and virtually all ecosystem indicators now show signs of recovery (*5*), suggesting that the Black Sea has returned to a healthier state. The rapid recovery of this large inland sea is encouraging for other marine ecosystems, most notably that of the Caspian Sea, which is itself currently under threat.

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Despite its relatively large surface area (423,500 km^2) and water volume (537,000 km^3), only a thin surface layer (about 10% of the average total depth) of the Black Sea supports eukaryotic life. The water mass below 150 to 200 m is devoid of dissolved oxygen, making the Black Sea the largest anoxic body of water in the world. Such anoxic conditions, exacerbated by limited water exchange with the Mediterranean, render the Black Sea extremely vulnerable to anthropogenic effects. The Black Sea is bounded by a narrow coastal strip along the southern and eastern coasts, and its northwestern region (covering about 25% of the entire basin) has a wide continental shelf with a depth of less than 200 m. Three rivers—the Danube, the Dnieper, and the Dniester—fed by a drainage basin of >2 million km^2 in the northwestern/northern region are responsible for about 85% of total riverine input to the Black Sea (about 340 km^3/year) (*1*).

In the 1970s and 1980s, increased nutrient input via the major rivers during the agricultural revolution in Iron Curtain countries resulted in strong eutrophication of the shallow northwestern/northern Black Sea. The concentration of inorganic phosphorus and nitrogen measured at the mouth of the Danube increased from 0.3 μM and 1.6 μM, respectively, during 1960–1970 to 6.4 μM and 13.6 μM, respectively, during 1976–1980 (*6*). Although phosphorus and nitrogen increased, the amount of silicon decreased (from 36.7 μM to 30.6 μM). Given that silicon has a strong affinity for particulate matter in sea water, this decrease seemed to reflect a diminution of solid flow due to the numerous dams built on the Danube and its tributaries (*7*).

Differential changes in the quantities of these essential nutrients were accompanied initially by alterations in the composition and quantity of pelagic primary producers (phytoplankton) and later of other food chain components. There were several adverse events in the northwestern/northern Black Sea, but not eastern coastal and deep regions—there was an increase in number and peak abundance of phytoplankton blooms including several red-tide events (*7*), modification of the phytoplankton composition in favor of flagellates (*6*), decreased oxygen concentration and expansion of hypoxia (*3*), reduced transparency of the water column (*8*), a decrease in nongelatinous zooplankton (*9*), mass mortality among the entire benthos (*4*), demersal and pelagic fish populations (*10*), and a decrease in overall biodiversity (*3*).

During the summer of 1978–1986, the mean surface chlorophyll concentration in the northwestern/northern Black Sea exceeded that in deeper regions by a factor of about 18, a difference clearly visible from satellite data (*11*). Despite increases in the northwestern/northern regions of chlorophyll a (evaluated by Secchi disk depth, a measure of the water's transparency), inorganic phosphate, primary production and phytoplankton biomass (*12*), there were no reports of dele-

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