Pliocene Role in Assessing Future Climate Impacts

Future warming projected by the Intergovernmental Panel on Climate Change (IPCC) has the potential to affect each of us. Extreme weather events, rising sea level, and migrating ecosystems and resources may result in socioeconomic stresses. Although we can plan and prepare for what is expected, the most dangerous aspect of our changing climate is the uncertainty in climate sensitivity.

To reduce the uncertainties of climate change, paleoclimatologists are focusing on a possible yet imperfect analog to a future warmer climate. The middle part of the Pliocene epoch, approximately 3.3–3.0 million years ago, is the most recent period in Earth's history in which global warmth reached temperatures similar to those projected for the end of this century, about 2°–3°C warmer globally on average than today [*IPCC,* 2007]. Unlike earlier warm periods such as the Late Cretaceous (approximately 100–65 million years ago), the mid-Pliocene was similar to today in terms of the positions of the continents and oceans and atmospheric carbon dioxide (CO_2) concentrations, but global warmth was distributed differently During the mid-Pliocene, temperatures at high northern latitudes, above 70°N, were as much as 10°–20°C higher than today, but tropical temperatures were near the same. The much warmer mid-Pliocene climate, then, has the potential to unlock the secret to climate sensitivity. The past may indeed be the key to the present.

The Mid-Pliocene

The mid-Pliocene is attractive for the analysis of future warming because it is geologically recent and therefore similar to today in many aspects. The land-sea configuration and continental positions were effectively the same as at present, and the basic patterns of ocean circulation and faunal and floral distributions were similar, though slightly altered. Mid-Pliocene sediments containing fossil proxies of climate are abundant worldwide, and sediment ages are easily determined. Many mid-Pliocene species are extant, making faunal and floral paleotemperature proxies based on modern calibrations possible. In addition, the intensity of sunlight incident on Earth and the atmospheric concentration of CO_2 were in the range of today's values. These similarities to present day allow us to understand mid-Pliocene climate, from both data and modeling perspectives, in the framework of modern climate.

The mid-Pliocene is not, however, a perfect analog for future climate. During the mid-Pliocene, the Earth was significantly warmer and sea level was about 25 meters higher than today [*Dowsett,* 2007]. Continental glaciers were absent from the Northern Hemisphere, and Florida and the West Antarctic peninsula were below sea level. Also, many geographic features such as the Great Lakes were not part of the landscape. More important, climate system response was dominated by the 41,000-year period of Earth's obliquity rather than by the 100,000-year period of eccentricity that has governed the more recent waxing and waning of Northern Hemisphere ice sheets. Furthermore, rather than trending toward warmer conditions, the mid-Pliocene is the last interval of sustained warmth in the prolonged cooling transition from the much warmer early Pliocene to the late Pleistocene ice ages.

Data Synthesis and Model Simulation

Numerous researchers utilizing a variety of fossil groups and techniques to determine paleotemperatures have documented and quantified global mid-Pliocene warmth. Traditionally, past sea surface temperatures (SST) have been estimated from counts of microfossils, and vegetation distribution has been reconstructed from fossil pollen (Figure 1). These techniques form the core of paleoclimate reconstructions, but more recent paleothermometry techniques based on magnesium/calcium in foraminiferal shells and alkenone unsaturation indices are expanding mid-Pliocene SST coverage into underrepresented geographic areas. Utilizing all available proxies of paleoclimate reduces the overall error of mid-Pliocene SST estimation compared with results based on a single proxy, and it expands SST estimation into regions where one or more proxies are not suitable. For example, planktic foraminifera are sparse or absent in the high latitudes, and alkenone-based techniques are ineffective in the warm tropics.

Proxy data document dramatic differences from modern conditions in some regions and similarities in others. At high latitudes, mid-Pliocene SSTs were substantially warmer than modern SSTs (Figure 2). These warmer conditions were reflected in the vegetation of Iceland, Greenland, and Antarctica [*Dowsett,* 2007], suggesting increased oceanic heat transport to the poles. Temperatures in the tropics were similar to modern temperatures, with one exception. In the equatorial Pacific, temperatures in the east were warmer than they are today such that normal mid-Pliocene surface conditions emulated a modern El Niño event; this brings into question the constancy of the modern SST gradient across the equatorial Pacific through time [*Wara et al.,* 2005]. Finally, at western continental margins including the equatorial Pacific, upwelling zones were characterized by warmer yet nutrient-rich waters, perhaps resulting from warming of high-latitude source water [*Dekens et al.,* 2007].

The Pliocene Research, Interpretation and Synoptic Mapping (PRISM) Group of the U.S. Geological Survey (USGS) has reconstructed global surface conditions including SST, sea ice extent, vegetation, land ice extent, topography, and sea level in a narrow temporal window. This effort provides boundary conditions for a series of atmosphere-only general circulation model (GCM) simulations. An additional three-dimensional data set of mid-Pliocene deep ocean temperatures, combined with the surface conditions, is now being used to initiate fully coupled ocean-atmosphere GCM simulations.

The first mid-Pliocene GCM simulations established that period as having been at least 2°C or 3°C warmer than the late twentieth century. The warming, forced by unchanged tropical SSTs and only modest CO_2 increases, was driven primarily by high-latitude components of the system. One example is the ice-albedo feedback, which resulted from extreme warming of high-latitude oceans and the consequent reduction in sea ice, land ice, and snow cover [*Chandler et al.,* 1994; *Sloan et al.,* 1996].

The first coupled ocean-atmosphere simulations of the Pliocene, unfettered by specified SSTs, revealed the enduring difficulty of models to simulate the warmth of the polar regions while maintaining nearly modern tropical temperatures. An increase in CO_2 to 400 parts per million in the simulations, still within the error bar for the mid-Pliocene, improved high-latitude SST comparisons but increased tropical temperatures as well [*Haywood and Valdes,* 2004]. The inability of models to simulate increased temperatures of polar regions without increasing tropical temperatures is not unique to the Pliocene. Discussion surrounding the stability of mid-Pliocene tropical temperatures continues, and the model-data discrepancy remains unresolved.

Another conundrum is the extreme warming of the North Atlantic Ocean during the mid-Pliocene. Independent studies relate this feature to increased North Atlantic meridional overturning circulation [*Raymo et al.,*

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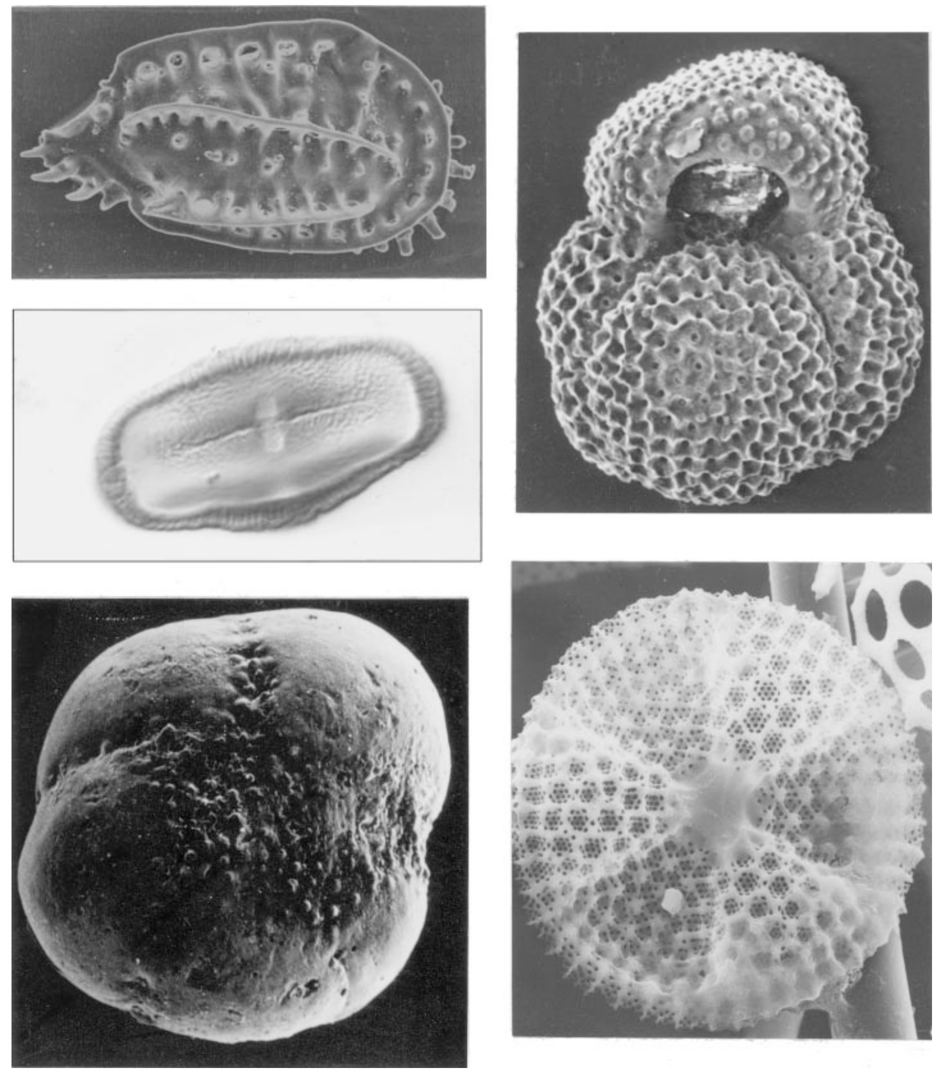

Fig. 1. Microfossils used in mid-Pliocene paleoclimate research. Clockwise from top left: ostracode, planktic foraminifer, diatom, benthic foraminifer, and pollen grain

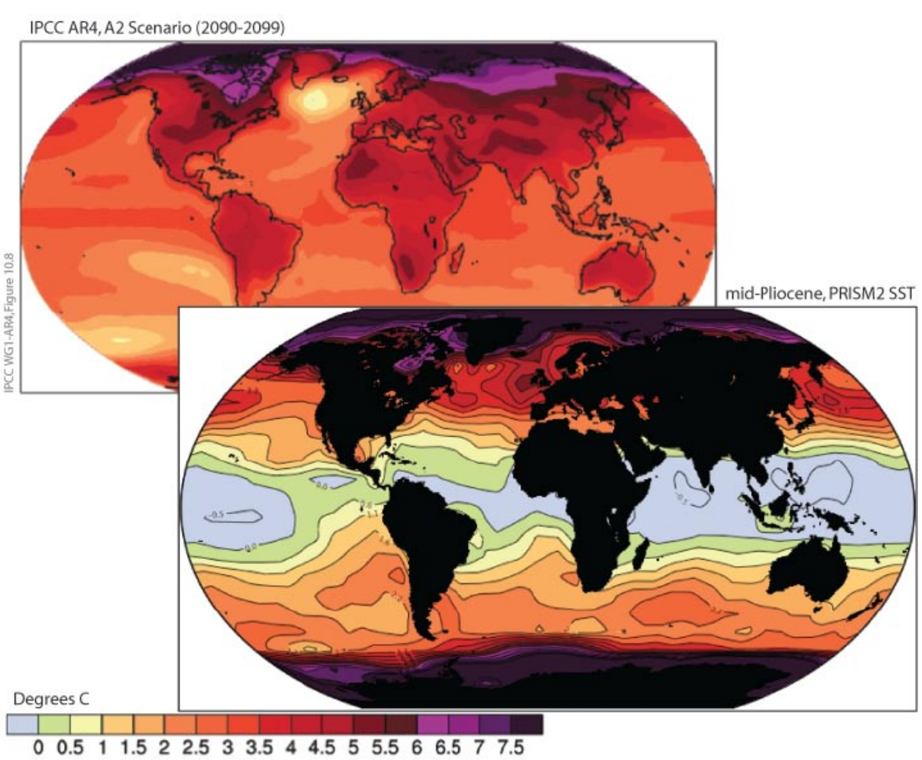

Fig. 2. Surface air temperature anomalies of (top) the late 21st century and (bottom) the mid-Pliocene.

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1996]. However, coupled ocean-atmosphere GCM simulations show that overturning decreases when simulations are forced by mid-Pliocene surface conditions. Either the mid-Pliocene equilibrium state of meridional overturning circulation and North Atlantic SST is very different from our future climate, or coupled ocean-atmosphere GCMs are wrong in this region.

Despite an impressive spatial network of mid-Pliocene environmental data, the cause of mid-Pliocene warmth remains unclear. Obvious suspects include increased greenhouse gas concentrations and increased meridional ocean heat transport, but neither cause has been explicitly proven. Also unknown are the strength of the mid-Pliocene thermohaline circulation, the pattern of global deep ocean circulation, and the effects of reduced land and sea ice.

Future of Mid-Pliocene Research

The mid-Pliocene data synthesis community has enjoyed a coevolutionary relationship with climate modelers extending back at least 14 years, with new paleoenvironmental data becoming available as new generations of models require it. The data serve as important ground-truthing measures for the models, and unexpected model results often lead paleoclimatologists to intriguing scientific questions that require expanded data coverage or the development of new proxies. This mutually satisfying data-model relationship continues and promises to expand.

As an example, a Pliocene Model Intercomparison Project planning workshop was held in June 2008 at the NASA Goddard Institute for Space Studies, in New York. There, paleoclimatologists and climate modelers discussed the logistics of cooperatively using the PRISM data sets to initialize modeling runs on a diverse array of models. As the model intercomparisons begin, scientists from across the globe are preparing to meet next summer to discuss their results of all aspects of mid-Pliocene climate. The data-model relationship will continue as preliminary model results will be presented and compared, and future research will be defined.

Collaborations between paleoclimatologists and climate modelers provide a better understanding of mid-Pliocene climate dynamics as well as improved model capabilities through the comparison of model results. Results from these initial comparisons will highlight the importance of continuing the iterative process of data synthesis and model simulation, and will further our understanding of the mid-Pliocene and also of future warm climates and their impacts.

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Author Information

Marci M. Robinson and Harry J. Dowsett, U.S. Geological Survey, Reston, Va.; E-mail: mmrobinson@usgs.gov; and Mark A. Chandler, NASA Goddard Institute for Space Studies, Columbia University, New York, N.Y.