Temperature changes in the tropics. If so, the Mg/Ca data provide an important constraint on the sensitivity of temperature changes to greenhouse forcing, which is of value in calibrating model predictions of future change in response to human-enhanced greenhouse forcing (Lea, 2004, 2006). In this scenario, a plausible chain of climatic linkages may be that rising atmospheric CO$_2$ warmed the tropical oceans, which in turn triggered northern-hemisphere deglaciation, resulting in sea level rise and other impacts. A competing idea suggests that warming of the southern and tropical oceans at 19 ka BP reflected a rapid adjustment of global oceanic heat transport to an early deglacial meltwater event in the North Atlantic, which also initiated sea level rise, followed by CO$_2$ rise (Clark et al., 2004). Proof of mechanism depends critically on the timing of events. With current chronologies, tropical warming started at 19 ka, whereas CO$_2$ rise began at about 18 ka (Ahn et al., 2004). Synchronizing the ice-core and marine records remains an important challenge that warrants further study.

Before either of these causal chains can be accepted, we must consider other paleotemperature proxies from the tropical Pacific. For example, new data on the alkenone $U_{27}'$ paleotemperature proxy from a high sedimentation-rate site near Galapagos (Y69-71, Prahl et al., 2006) imply cooling during early deglaciation ($\sim$20–15 ka) at just the time that Mg/Ca implies warming to modern temperatures (Fig. 1a). A similar pattern of deglacial cooling in $U_{27}'$ temperature records has been found in the South China Sea and has been associated with a response to Heinrich Event 1 (Kiefer and Kienast, 2005). The differences in absolute temperature estimates are as much as 3°C, too large and systematic to be explained by random analytical errors, and the differences in timing are much larger than can be explained by chronological errors. Can we reconcile the apparent conflict between these paleotemperature proxies?

One possibility is that the two proxies are biased by different seasonal or interannual variations. If warm-loving foraminifera preferentially lived during seasonal or interannual warm states (such as El Niño), whereas the phytoplankton that make alkenones favored more productive seasonal or interannual cool states (such as La Niña),
the apparent conflict would be resolved. Indeed, one model predicts anomalously high ENSO variance between ~20,000 and ~11,000 years ago (Clement et al., 1999), coincident with high contrast in the two paleotemperature proxies (Fig. 1b). But the relationship is less convincing at greater ages, suggesting that seasonal or interannual bias is not the primary cause of the disagreement.

Another possibility is that one or both of the paleotemperature proxies are biased by underlying oceanographic conditions. The $U_{37}^{\delta}$-Mg/Ca temperature differences are surprisingly well matched to stable carbon isotope signatures ($\delta^{13}C$) in the thermocline-dwelling planktonic foraminifera, Neogloboquadrina dutertrei (Fig. 1c). The low $\delta^{13}C$ event that occurs during the deglacial transition from ~20–15 ka is thought to represent the re-initiation of thermohaline circulation and a transfer of water masses that are rich in nutrients and dissolved inorganic carbon from the deep sea to the upper ocean (and CO$_2$ to the atmosphere) via the Antarctic circumpolar ocean and subsurface mode waters that form in the sub polar regions and eventually contribute to tropical upwelling systems (Spero and Lea, 2002).

Might the $U_{37}^{\delta}$ temperatures be too cold during the deglacial transition? Prahl et al. (2006) note that in isothermal cultures, nutrient stress can induce the appearance of cooling of the $U_{37}^{\delta}$ index. This effect is associated with a change in the ratio of the C36 alkenoate in its ethyl relative to methyl ester forms (EE/ME). Indeed, the EE/ME index appears to correlate with the $U_{37}^{\delta}$-Mg/Ca temperature differences in tropical Pacific sediments (Fig. 1d), and this opens the possibility that the lag of $U_{37}^{\delta}$ warming behind that of Mg/Ca may reflect ecological bias on $U_{37}^{\delta}$. It is curious, however, that organic geochemical evidence for low-nutrient stress would be associated with low $\delta^{13}C$, which in these sites is likely associated with high nutrients. An alternate solution may be one of habitat, i.e., that the alkenone producers selectively occupied the high-nutrient thermocline water mass that was cooler than surface waters during the deglaciation. So rather than a firm answer, this presents yet another puzzle worthy of further exploration.

The deglacial transition is also a time of anomalously high calcite preservation, associated with the adjustment of the whole-ocean carbonate system to the transient release of CO$_2$ from the ocean to the atmosphere (e.g. Marchitto et al., 2005). A preservation event (which roughly coincides with or slightly lags the deglacial $\delta^{13}C$ minimum in Fig. 1c) could induce a warm bias in the Mg/Ca temperatures during deglaciation. Lea et al. (2006) acknowledge the possibility of a time-varying dissolution effect on the paleotemperature record, but in the absence of consistent proxies for dissolution intensity they do not vary their dissolution corrections through time. In spite of many efforts, proxies for carbonate dissolution are at best qualitative, so it is difficult to say just what corrections might apply to Mg/Ca. Lea et al. make the excellent point that the early rise of temperature in the Mg/Ca data are
now found throughout the tropics and in parts of the South Pacific, and in several different proxies including foraminiferal and radiolarians, and this suggests that time-varying dissolution corrections on Mg/Ca are small.

As illustrated here, each of the proxies for paleotemperature has proven to be a bit more complicated than originally expected. Nevertheless, with the advent of multi-proxy studies the paleoclimate community has made great progress, notwithstanding spirited discussion. Most workers now agree that significant ice-age cooling occurred throughout the tropics, and this is a real constraint on the sensitivity of climate models. Although we do not yet understand all the difference between temperature proxies, the findings that the differences are systematic and in some way related to identifiable oceanic processes offer hope that progress will come from careful intercomparison of data sets, including those related to nutrients and preservation. The careful analytical work documented here by Lea et al. paves the way for new understanding as the community approaches this multi-proxy task with open mind. That, and establishing firm chronological constraints that link ice core and marine records into a unified framework, offer the promise of understanding mechanisms of major climate change in a way that cannot be addressed with historical records.

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