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CLIMAP SSTs re-revisited

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Abstract Since the 1976 publication of the CLIMAP ice age sea surface temperature (SST) reconstruction showing a 1–2 °C tropical cooling a substantial debate has arisen as to whether tropical SSTs may instead have been 4–5° colder than present. Herein I review the arguments for large SST variations and question a number of key findings, particularly the validity of ice-age coral SST estimates and "down-projecting" tropical snowline changes to the surface. GCM results indicate that an intermediate solution requiring ~2.5 °C warm pool cooling is consistent with most quantitative low elevation surface land data and is small enough to allow the persistence of tropical biota in the ocean during glacial times. The proposal reduces estimated ice-age climate sensitivity (for a doubling of CO_2) from a "high-end" sensitivity of about 4.5 °C (for a 5–6 °C tropical cooling) to a "mid-range" sensitivity of about 3.0 °C for a 2.5 °C warm-pool decrease.

1 Introduction

One of the most important problems in paleoclimatology involves the magnitude of sea surface temperature (SST) changes during the last ice age. CLIMAP (CLIMAP Project 1976, 1981) was the first group to systematically estimate SSTs for the last glacial maximum, and concluded that tropical SSTs were about 1.5 °C below present. These boundary conditions have served as the basis for a whole suite of simulations of the climate of the last glacial maximum (e.g. COHMAP Project 1988; Gates 1976a, b; Kutzbach and Guetter 1986; Kutzbach et al. 1993).

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However, even before CLIMAP there were alternate estimates of the magnitude of the tropical SST changes. Emiliani (1971, 1995) combined observations of faunal variations with oxygen isotope studies and calculations of the isotopic composition of ice sheets to propose a much greater change, on the order of 5 °C for the tropical Atlantic and 3–4 °C for the eastern equatorial Pacific. Although Emiliani's (1971, 1995) contribution has generally been neglected in subsequent discussions of this issue, its essence was resurrected when Webster and Streeten (1978) pointed out that from atmospheric lapse rate considerations, small SST changes in the tropics are seemingly incompatible with freezing line reductions of about 1 km on New Guinea and other tropical glaciers. Rind and Peteet (1985) revisited this problem with a general circulation model (GCM) simulation and more detailed assessment of the tropical sites and reached the same conclusion. Broecker (1997) summarized more recent evidence and, after adjusting for a 120 m sea level drop (Fairbanks 1989), concluded that a mean corrected snowline lowering of about 800 ± 50 m occurred. Assuming a constant lapse rate would still require about a 4 °C tropical cooling.

Despite these developments, continued testing of the CLIMAP transfer function method (Prell 1985) supported the original CLIMAP conclusion, although later refinements suggested that reconstructed SSTs in some areas, such as the Coral Sea and the central North Pacific, may underestimate the actual glacial SST changes (Anderson et al. 1989; Lee and Slowey 1999). Research stagnated at this stage for a number of years until a series of papers published in the early 1990s jolted the paleoclimate community by raising serious questions concerning the validity of the CLIMAP SST reconstruction. One involved last glacial maximum temperature estimates obtained from measurements of noble gas concentrations in groundwater at tropical sites (Stute et al. 1992, 1995). These gases do not interact with dissolved groundwater species, making their concentration primarily a function of the local mean annual surface temperature. Measurements from a number of tropical sites suggest groundwater temperature reductions of about 5 °C for the last glacial maximum (Fig. 1), a result seemingly incompatible with CLIMAP SST changes of only 1–2 °C.

A second line of contrary evidence involved geochemical measurements of corals from the last glacial maximum or shortly thereafter (Beck et al. 1992, 1997; Guilderson et al. 1994). Comparisons of the present seasonal cycle of temperatures with observed changes in oxygen isotope or Sr/Ca ratios from recent coral samples generally indicate correlations on the order of 0.8–0.9. Application of this geochemical calibration to ice age or late glacial coral samples again yields estimated mean annual SST changes on the order of 5 °C (Fig. 2). These results appeared to confirm the similar conclusions from snowline changes and groundwater studies.

Given these new lines of evidence, is it any wonder that there seems to have been a sea change in opinions about the magnitude of ice age cooling? If these were the only points to consider most investigators would conclude that CLIMAP was simply wrong. But additional considerations lead me to propose that such a conclusion is too extreme, and that a more satisfactory conclusion is that CLIMAP SSTs may be somewhat too warm but not nearly as much as is suggested by the snowline, coral, and groundwater data.

There are two main reasons why it is important to resolve the problem of the magnitude of ice age SST change: (1) it is always important to try to reconcile various lines of evidence, both among the different data sources and between data and models; (2) resolution of the problem has significant implications for trying to assess the sensitivity of the climate system to radiative perturbations (Crowley 1994). If ice age tropical SSTs decreased by 5 °C, especially in Indo-Pacific regions far removed from the cooling effect of ice, an almost inevitable conclusion is that climate sensitivity is relatively high, on the order of 4.5 °C for a doubling of CO_2

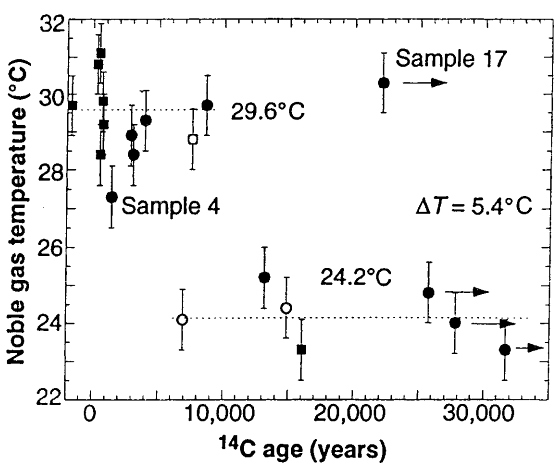

Fig. 1 Groundwater based temperature estimates for the present and last glacial maximum from eastern Brazil (from Stute et al. 1995). The results suggest a 5 °C temperature decrease for the last glacial maximum

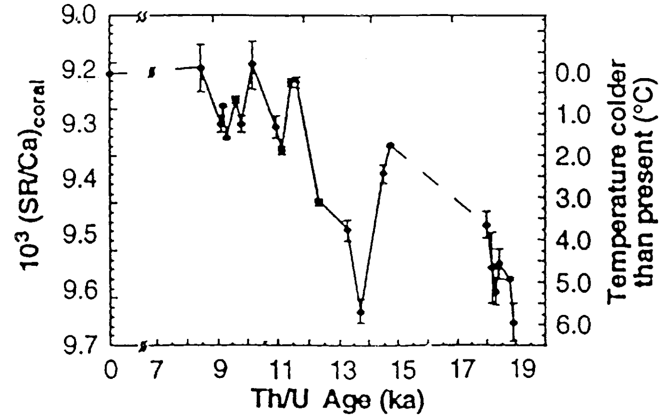

Fig. 2 Glacial–interglacial SST changes for a Caribbean coral estimated from two geochemical methods, Sr/Ca and oxygen isotope ratios (from Guilderson et al. 1994). The results suggest a 5 °C temperature decrease for the last glacial maximum for this site

(Crowley 1994). This value is at the extreme high end (Kattenberg et al. 1996) of estimates from the Intergovernmental Panel for Climate Change (IPCC). If CLIMAP is right, then climate sensitivity may be only 2.0–2.5 °C (Hoffert and Covey 1992; Hyde et al. 1989).

I re-examine the problem of ice age tropical SSTs and propose that, despite the growing body of evidence apparently demanding a major reappraisal of CLIMAP SSTs, an alternate explanation can be advanced that calls for an intermediate conclusion wherein SSTs may have been on average about 1.0–1.5 °C cooler than CLIMAP but still significantly warmer than those predicted by groundwater, corals, and tropical snowlines. This alternative results in an intermediate sensitivity estimate of about 3.0 °C to the climate system. The approach adopted here is to first briefly discuss some background with respect to proxy temperature methods, then review the present state of the evidence on a discipline-by-discipline basis, and finally to discuss new modeling results relevant to the proposed reconciliation. I conclude with a proposed resolution to some of the problems discussed and examine the implications for climate sensitivity and the "tropical thermostat."

2 Background to the transfer function method

The CLIMAP group studied the distribution of plankton in marine sediments in both core top (representative of the last 1000–2000 years) and glacial maximum samples (18 000–21 000 BP, years before present). Regression of core top plankton assemblages against modern SSTs generally indicate correlations on the order of 0.8–0.9 (e.g., Kipp 1976; Prell 1985). CLIMAP employed a "total faunal analysis" (Imbrie and Kipp 1971), in which percentage counts of all species (mainly foraminifera in the tropics) present are included. The dimensionality of the "core top" data set is first reduced by the use of empirical orthogonal functions (EOFs) to isolate the most significant contributors to SST variability. The EOFs are then regressed against modern SSTs, with past SSTs estimated based on the downcore EOF composition of samples, assuming that identical samples are indicative of identical SSTs.

CLIMAP 1981 results indicate that on average tropical SSTs decreased only about 1.5 °C, although larger cooling was estimated along eastern boundary currents and equatorial upwelling zones. Average cooling in the western equatorial Pacific was 1.1 °C (i.e., 20°N to 20°S, 130°E to 170°W north of the equator, and 150°E to 170°W south of the equator). This huge area ($26 \times 10^6\,km^2$), the core of the warm pool, is comparable in size to the area of expanded ice during the last glacial maximum.

Although any number of questions can be raised about the validity of the estimates, the basic reason the equations predict small temperature changes is that the biotic variations on which they are based also indicate relatively little change. An example is a record from the Sargasso Sea (27°N) in the North Atlantic (Fig. 3) which illustrates estimated winter and summer temperatures along with the oxygen isotope and carbonate curves used for stratigraphic correlations in a core that is little affected by carbonate dissolution (see later) (Crowley and Matthews 1983). Also shown is a plot of the abundances of the tropical downcore factor (empirical orthogonal function) loadings. Squaring this value yields the amount of variance explained by that factor (Imbrie and Kipp 1971). This factor accounts on average for about 80% of the variance in the entire core. Since it does not change much, neither do the estimated temperatures. This is the basic reason for the stable SST estimates in the CLIMAP reconstructions.

Additional objections have been raised about the CLIMAP method itself rather than the data it is used to process. The validity of the method has been called into question given the results of numerous plankton studies suggesting that abundances could be influenced by factors other than temperature (e.g. nutrients, including micronutrients such as iron that could affect their food source). However, a usually overlooked assumption of the Imbrie–Kipp (Imbrie and Kipp 1971) method used by CLIMAP is that plankton estimates are dependent on temperature or factors linearly related to temperature. Another criticism involves how some species abundance changes are not reflected in SST estimates (e.g., Emiliani 1995). While this could reflect a weakness in the method, it could also simply indicate that some species do not correlate well with SST. As such, their variations would have little weighting in the regression equation.

Within the basic concept of tropical stability there is still room for uncertainty with respect to CLIMAP SST estimates. For example, three species of foraminifera disappeared in the Atlantic during the last glacial maximum (Ericson and Wollin 1956). However, all these species were subsurface dwellers, so it is not clear how such changes reflect SST variations (see earlier). The species changes could well reflect nutrient level changes in the thermocline (Ravelo et al. 1990), which again may not linearly correlate with SST (see earlier). Of somewhat more concern is that the average size of some species also changed (Emiliani 1969, 1995), suggesting that surface water conditions were somehow different. Even in the record illustrated (and other cores), a key mixed layer warm water species (*Globigerinoides sacculifera*) was reduced in abundance during the last glacial maximum (Crowley and Matthews 1983; Curry and Oppo 1997).

More serious concerns about the CLIMAP SST reconstruction involve the distribution of samples in the Pacific being much patchier and sparser than in the Atlantic, leading to greater uncertainties with respect to the quality of the SST reconstruction in this vast basin. This problem is highlighted by a recent model-data comparison (Broccoli and Marciniak 1996) indicating that Atlantic CLIMAP SSTs agree fairly well with a mixed layer ocean model calculation, whereas CLIMAP Pacific SSTs are too warm. The Pacific problem is compounded by glacial-interglacial changes in calcium carbonate dissolution, which can selectively alter plankton abundances (Berger 1970). For example, increased Holocene dissolution in the Pacific could remove more fragile mixed-layer species, thereby potentially reducing the glacial–interglacial amplitude of fluctuations (Berger 1997; Erez 1979; Le and Thunell 1996). This conjecture is supported by new evidence (Lee and Slowey 1999) from very shallow cores near Hawaii suggesting that glacial SSTs were about 2 °C less than present, significantly less than the 2–3 °C positive anomalies estimated by CLIMAP. However, the revised SST estimates in the new study do not come anywhere close to 5 °C, even at 23°N.

Another problem involves the choice of a transfer function for converting faunal abundances to SST. An alternate approach to the Imbrie–Kipp method (Imbrie and Kipp 1971) of estimating SSTs is to bypass the EOFs and make a direct comparison of percentage variations of different species with "nearest neighbors" in core tops. The basic idea behind this alternative is that empirical orthogonal functions might "muffle" faunal changes, thereby indicating apparent stability where none exists. An alternate approach to estimating SSTs, termed the "modern analog technique" (MAT) (Hutson 1979; Prell 1985), has also been applied to a slightly updated CLIMAP data base (Prell 1985). This method estimates downcore SSTs with core tops via a "nearest neighbor" scheme. Initial application (Prell 1985) of the MAT to the ice age case yielded a conclusion very similar to CLIMAP (CLIMAP Project 1981). However, since that effort the MAT has been modified in different ways (e.g., Ortiz and Mix 1997; Pfaumann et al. 1996; Waelbroeck et al. 1998) to give even more weight to the nearest neighbors (rather than, for example, linear weighting with distance). One objective of these modifications has been to reduce the standard error of estimate (on the order of 1.5 °C for CLIMAP) to less than 1.0 °C. Utilizing one of these modifications, Waelbroeck et al. (1998) concluded that cold-season SSTs in the Atlantic might

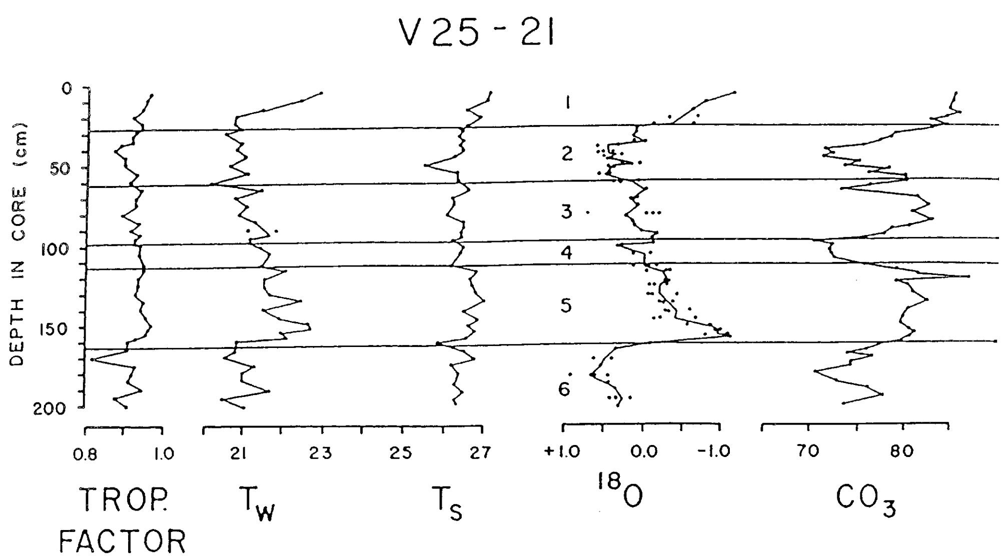

Fig. 3 Comparison of plankton and temperature changes over the last 160 000 years from a Sargasso Sea core (Crowley and Matthews 1983). Faunal abundances (factor loadings) indicate abundance of tropical assemblage in the core (see text). Winter and summer temperatures estimated with the same equation utilized by CLIMAP (CLIMAP Project 1981). Oxygen isotope and carbonate variations plotted versus core depth. The record extends into the penultimate glacial maximum

have been 1–2 °C less than estimated by CLIMAP (Waelbroeck et al. 1998).

Mix et al. (1999) also estimate that CLIMAP SSTs were too warm in some tropical regions. These authors demonstrated that the communalities (a measure of a sample's similarity to calibration faunas) of many tropical foraminiferal assemblages in the ice age are lower than required by the Imbric and Kipp (1971) transfer function. An alternate approach emphasizing more the abundance of rarer species resulted in an additional 1–2 °C cooling in tropical Atlantic and eastern Pacific sites. This approach was at one time rejected by Imbrie et al. (1973) on the basis of increased sampling errors for rare species, but a lognormal adjustment by Mix et al. (1999) may have circumvented the problem. These authors found that the largest ice-age cooling (with respect to CLIMAP) occurred along eastern boundary currents and upwelling zones, areas that even the original CLIMAP Project (1976) estimates mapped as having large changes. The overall cooler conditions had a significant impact on model-generated temperatures over land (Hostetler and Mix 1999). However, western Atlantic cooling was only 1 °C more than CLIMAP, and gyre center SSTs were unchanged or even slightly warmer. Thus, the basic problem of warm pool SST changes is relatively unaffected by the Mix et al. (1999) results.

Similar conclusions result from geochemical analyses of plankton in marine sediments. Alkenone compounds are long-chained hydrocarbons derived from marine plankton that are correlated with SST variations. Application of alkenone paleothermometry to a number of tropical ice age sites (Bard et al. 1997; Ohkouchi et al. 1994) suggests relatively stable tropics, but with SST changes slightly colder (0.5–1 °C) than CLIMAP; in other words the alkenones, if correct, permit about an average 2.0 °C change in tropical SSTs during the ice age. However, there are some concerns about whether the alkenone calibration may be nonlinear at temperatures greater than 22 °C (Conte and Weber 1998; Sonzongi et al. 1997), so continued uncertainties persist with respect to this technique.

SSTs can also be estimated from $\delta^{18}O$ and Mg/Ca variations in marine plankton. Most Atlantic low latitude oxygen isotope variations are on the order of 1.75‰. After subtracting a glacial-interglacial ice volume effect of about 1.3‰ (Chapell and Shackleton 1986), Broecker (1986) estimated that the SST variations were on the order of 2 °C for the tropical Atlantic and close to 0 °C for the tropical Pacific. It is conceivable that some of these numbers may have been affected by low sedimentation rates and the dissolution problems discussed already (Erez 1979). For example, Curry and Oppo (1997) found a larger 2.2‰ shift in one western Atlantic site that was interpreted as a 4 °C cooling. However, plausible corrections for a salinity overprint lowered this number to about 2.5 °C (Wolff et al. 1998). A virtually identical 2.5 °C estimate (Fig. 4) for this region was derived from another paleothermometer, Mg/Ca variations in the foraminiferal crystal lattice (Hastings et al. 1998).

To summarize results from the transfer function approach, relatively small variations in plankton abundances through time are the basic reason for stable CLIMAP SST estimates within the tropical warm pools. Additional transfer function results since CLIMAP show some regional exceptions to this overall stability, e.g., 1–2 °C greater cooling along the Atlantic and Pacific eastern boundary currents and equatorial upwelling zones (Curry and Oppo 1997; Mix et al. 1999). Questions have existed since the advent of CLIMAP concerning issues of geographic coverage and dissolution in the Pacific, most significantly in regards to the large areas of positive CLIMAP anomalies there. Improved transfer functions and more data have removed many of these warm peaks (Anderson et al. 1989; Lee and Slowey 1999; Mix et al. 1999), with results more consistent with low-to-moderate (1–2 °C) ice age SST decreases. The new transfer function results are now more in line with geochemical data from plankton (alkenones, Mg/Ca ratios) suggesting 2–2.5 °C warm pool changes. Despite these changes over the last 20 years, I am not aware of any body of extensive, robust plankton data suggesting ice-age warm pool changes of 5–6 °C. These results prompt me to re-examine some of the other evidence for larger changes in the tropics (see later).

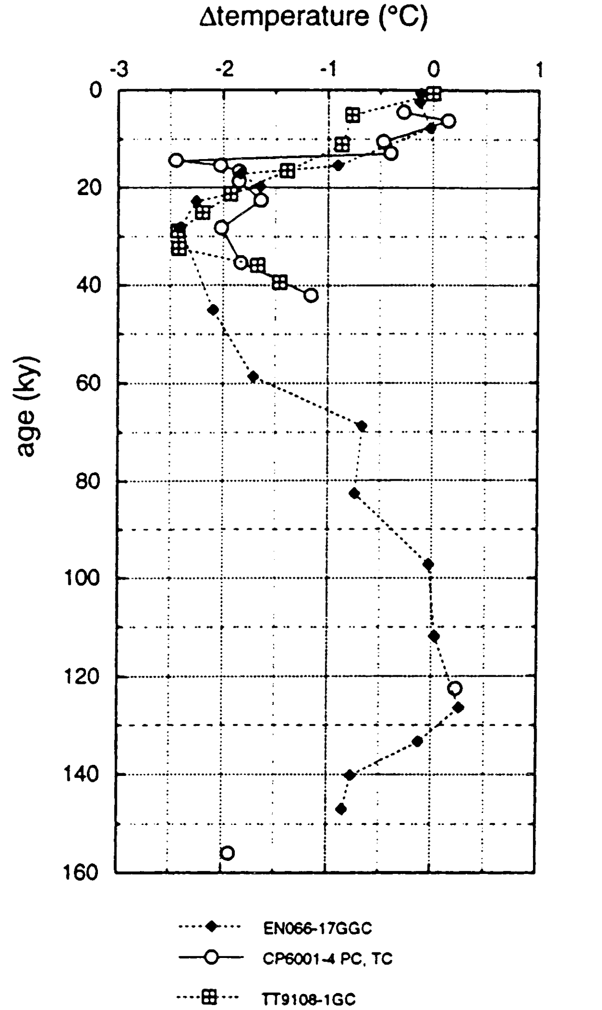

Fig. 4 Mg/Ca estimates (from plankton foraminifera) of glacial–interglacial SST changes in three different cores from the tropical Atlantic (from Hastings et al. 1998)

3 Re-assessment of evidence for large tropical cooling

In this section I will go through the various lines of evidence for 5 °C tropical cooling and discuss on a discipline-by-discipline basis my opinion of the validity of the evidence. At the end new modeling results will be discussed that attempt to reconcile marine and terrestrial data. My concerns regarding the various lines of evidence for ice-age cooling are:

1. A 5 °C cooling should have resulted in many more changes in biota than is observed during the ice age. Although biotic changes certainly occurred in the tropics (see earlier), the wholesale magnitude of changes required by a 5 °C SST change does not occur. In fact, as stated already, the very reason why the CLIMAP methodologies yield relatively stable SSTs is because of the relative stability of plankton populations.

Is it possible that biota have simply adapted to climate change, thereby effectively changing their calibrations to climate? This is theoretically possible, and the suggestion cannot be disproven (at least to my knowledge). However there are several mitigating arguments that suggest such a possibility is unlikely:

a. Individual species of plankton have existed for hundreds of thousands to millions of years, to remain stable under the influence of dozens of glacial-interglacial climate fluctuations would require an unusually high level of "evolutionary plasticity", especially since the climate changes are primarily oscillatory and not secular (i.e., the adaptations would require some form of reversible, i.e., cyclic, genetic changes or adaptations to multiple stable states). Such changes are possible but additional objections listed also need to be considered.

b. Almost everywhere else, on land and sea, sometimes into the deep tropics (e.g., eastern boundary currents and equatorial upwelling regions), biota changed during the ice age, presumably in response to environmental changes. At present biota reflect the large-scale climate; if there were large biota changes in almost all regions during the ice age as the climate changed, why did warm-pool plankton not change along with their environment?

c. If planktonic groups are routinely used to verify abrupt climate change in the subpolar North Atlantic and elsewhere (e.g., Bond et al. 1993; McManus et al. 1994), why should they be used to support some hypotheses but rejected when they do not support other hypotheses? If the utility of plankton as paleoenvironmental indicators is to be questioned a minimal criterion for judging the issue should be an insistence on consistency of application.

d. If SST changes were 5 °C in the tropics, why were corals even there during the ice age? At present corals do not thrive in most waters 5 °C below the present temperature. For example, the present distribution of corals versus mean annual SSTs (Fig. 5) indicates that most corals are located in regions where mean annual SSTs are greater than 24 °C. Also shown in this figure is an illustration of the effects of a uniform 2.5 °C and 5.0 °C decrease in SSTs. It is quite clear that if tropical SSTs were 5 °C colder than present, most corals would be at the edge of or below their present limit of habitability. A histogram (Fig. 6) of coral distributions for different SST changes indicates that only 5% of present corals would be optimally adapted to SSTs 5 °C colder than present.

Even if corals adapted to tropical SST changes their environmental thermometers may have been reset. An occasionally unappreciated point involving coral paleotemperature estimates involves the observation that corals incorporate neither $\delta^{18}O$ nor Sr/Ca into their skeleton in the same ratios as in seawater. The sometimes dramatic differences in ratios are due to a process called "biological fractionation." For example, the $\delta^{18}O$ biological fractionation for Pacific corals in equivalent to 8–12 °C, Sr/Ca ratios in corals are about eight times the ratio in seawater, and some of the Sr in corals is in the form of strontianite ($SrCO_3$) rather than elemental substitution in the aragonite crystal lattice of the coral (Greegor et al. 1997). This topic is further discussed later.

Although it may be possible to rebut some of these objections in a piecemeal fashion, the most parsimonious explanation for the inferred stable plankton abundances is that SSTs decreased but did not decrease as much as indicated by the terrestrial data.

2. Paleotemperature estimates from pollen data may be suspect. In theory pollen data can be regressed against environmental variables and used to make the same type of temperature predictions for land as was done for the sea by CLIMAP (CLIMAP Project 1981). There are significant plant changes in the tropics for the glacial maximum (Adams et al. 1990; Crowley 1995), and some of these changes have been used to estimate as much as 5 °C change on land in low elevations (Colinvaux et al. 1996; Liu and Colinvaux 1985). But there are two reasons why these estimates should be taken with considerable caution: (a) in the cited studies no attempt was made to develop an objective transfer function relating pollen changes to environmental changes; it hardly seems consistent to use uncalibrated data from land to dismiss 25 years of conclusions based on the careful quantitative calibration and testing of marine plankton data (see Prell 1985); (b) where pollen transfer functions have been employed (Bonnefille et al. 1992; Guiot et al. 1989; van Campo et al. 1990), some question exists as to the validity of one of the basic assumptions of transfer functions (Imbrie and Kipp 1971), namely that the relation of biota to environmental forcing was the same in the past.

It may seem strange to invoke this argument, given the discussion on marine plankton. But one critical difference exists between marine plankton and terrestrial plant response to ice age climate change, terrestrial plants may also be sensitive to ice age CO_2 changes (Polley et al. 1993; Street-Perrott et al. 1997). Studies indicate that C3 (i.e., leafy) plants do not function well relative to C4 plants at ice age CO_2 concentrations (200 ppm) (Aucour et al. 1994). Vegetation reconstructions show C4 plants (e.g., some grasses) more abundant during the last glacial maximum (Crowley 1995). Thus vegetation changes at low elevations during the last glacial maximum cannot be automatically used to constrain ice age temperature levels. In transfer function terminology, this is known as a "no-analog" situation.

3. Tropical snowline fluctuations may not provide precise estimates of past SST change. This statement seems to fly in the face of the standard view of interpreting snowline data, but it is based on the simple observation that projections of snowline data down to the surface usually assume a constant lapse rate. If that lapse rate were to change only 20% even the CLIMAP SST field could be reconciled with the upper air data (Sun and Lindzen 1993). Is there any independent method to determine whether the lapse rates may have changed in the past? No good candidate comes to mind for the ice age case, but one can examine surface and snowline changes for other, smaller climate change

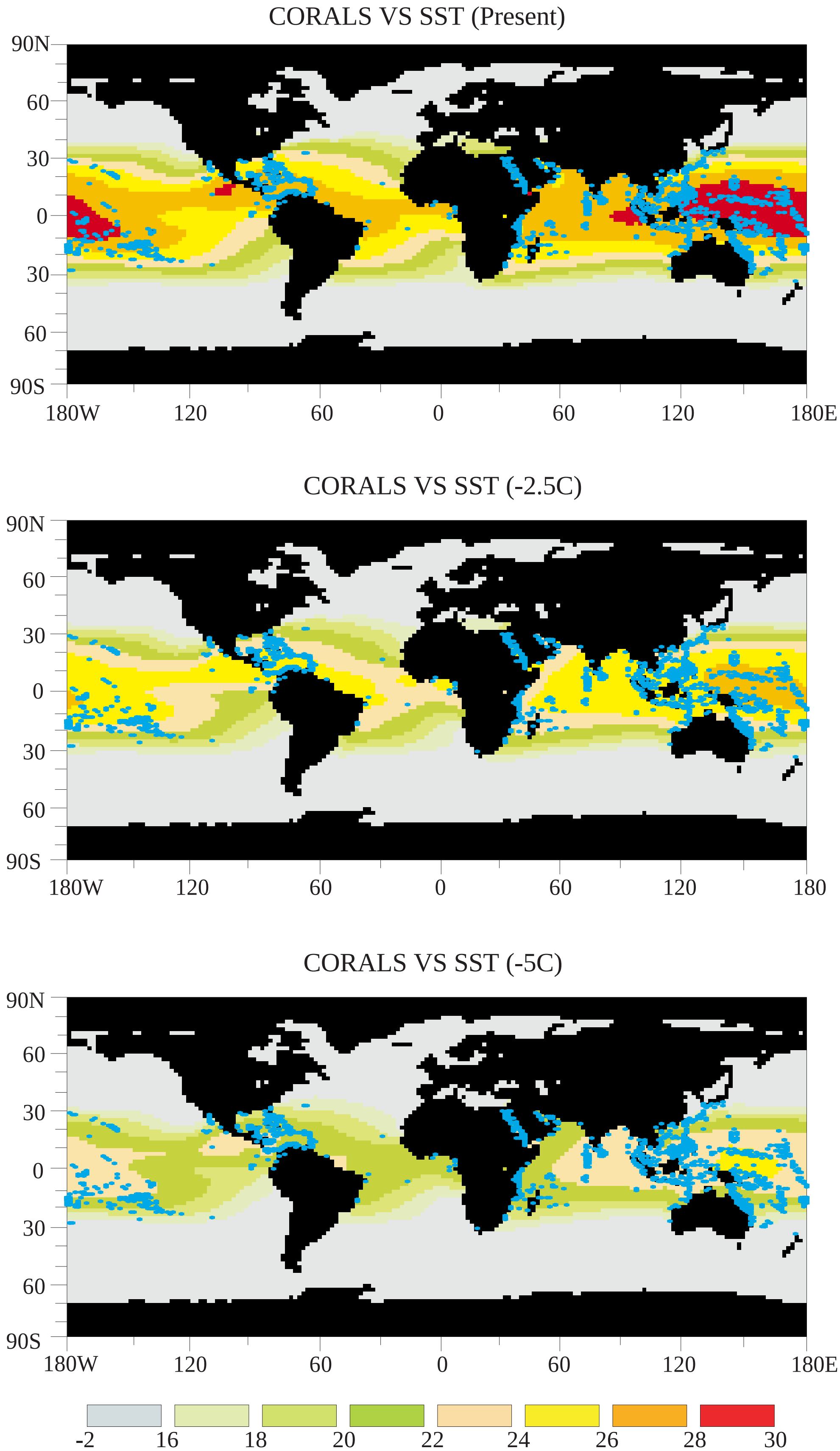

Fig. 5 Comparison of the present distribution of corals versus mean annual SST for (*top*) present; (*middle*) a 2.5 °C reduction in SSTs; and (*bottom*) a 5.0 °C reduction in SSTs. Most corals are on the edge or outside of their present range of distribution if SSTs had dropped 5.0 °C during the last ice age

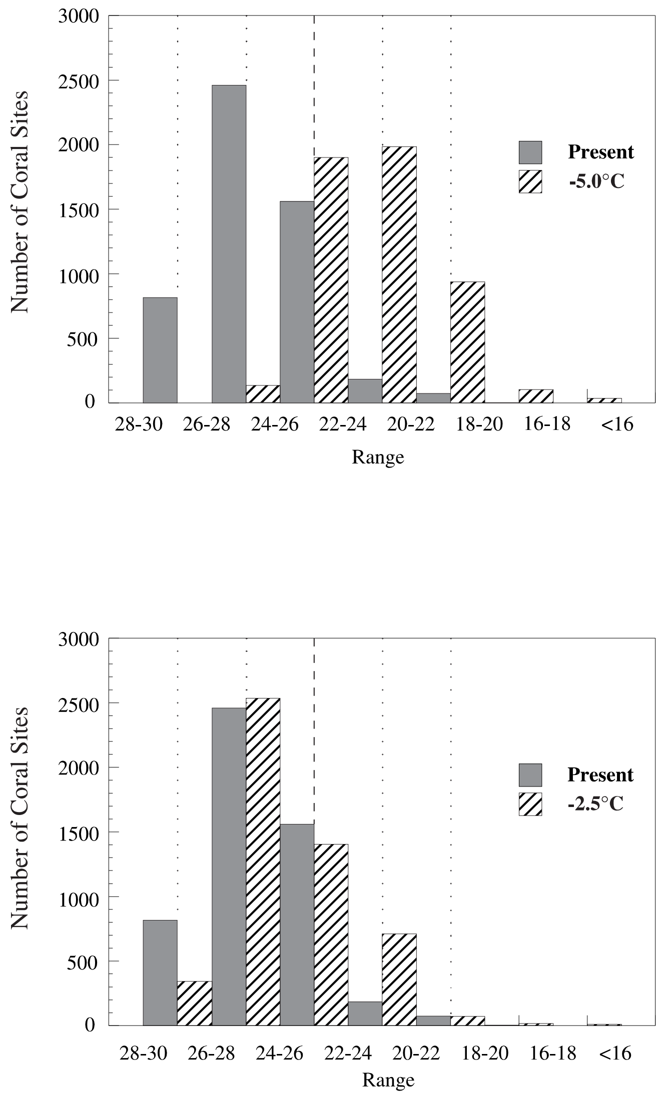

Fig. 6 Histograms of coral distribution versus SST (2 °C bins) for present and ice-age scenarios with (top) 5 °C uniform cooling; and (bottom) 2.5 °C uniform cooling. Of present corals 95% ($n > 4000$) live above mean annual temperatures of 24 °C; if ice-age SSTs were uniformly 5 °C lower, 95% of corals would be living in waters below mean annual temperatures of 24 °C

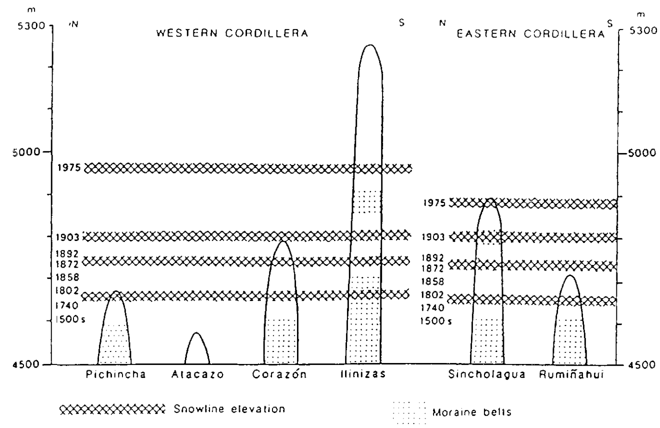

Fig. 7 Reconstructed snowline changes in the Andes over the last few centuries. Results from Hastenrath (1981); figure from Grove (1988)

scenarios. For example, during the peak of the Little Ice Age Northern Hemisphere cooling in the seventeenth century, snowlines in many areas decreased 250–300 m (Grove 1988). This snowline change even applies to the deep tropics (Fig. 7) of the Andes (Grove 1988; Hastenrath 1981). There are also several lines of independent data indicating Northern Hemisphere surface temperature change (Bradley and Jones 1993; Groveman and Landsberg 1979; Huang et al. 1997; Mann et al. 1998; Pollack et al. 1998). These approaches generally estimate that the peak cooling in the seventeenth century was about 0.4–0.7 °C less than the mid-twentieth century warm interval (Fig. 8).

Suppose we accept the larger hemispheric temperature change of 1.0 °C and furthermore assume that tropical changes are the same as the mean annual. These are extreme assumptions but useful as a test of concept. Utilizing the standard lapse rate approach to the Andes (Colinvaux et al. 1997) data (moist adiabatic in the tropics of about 5.5 °C/km), one would predict an average surface temperature cooling in the seventeenth century of about 1.5 °C, 100–300% larger than the global/hemispheric estimates of Pollack et al. (1998) and Mann et al. (1995). Yet increasing the lapse rate only 5% could reconcile the surface temperature changes with a 300 m snowline depression. Such a small change in the lapse rate seems hardly worth debating as a plausible alternate explanation for the observed surface and upper air changes.

An even more recent example supports this line of reasoning. Diaz and Graham (1996) have examined radiosonde-derived observations of freezing line changes over the last few decades in an attempt to verify observations of large and rapid snowline changes from tropical glaciers (Thompson et al. 1998). The potential confounding complications of hydrology and orography in interpreting snowline changes in mountainous regions are circumvented by these data, which indicate that the freezing line in the deep tropics has increased on the order of 110 m in association with the decadal-scale increase in global temperatures that began in 1976–1977. According to the standard lapse rate argument applied to the ice age case, such a freezing line change should be associated with a surface temperature change of about 0.6 °C, yet the observed tropical SST change is only on the order of 0.2–0.3 °C (Diaz and Graham 1996). Model results, even at relatively high resolution (T42), indicate that the simulated freezing line changes since 1976 agree only partially with observations (Diaz and Graham 1996). The model (ECHAM3) underestimates the freezing line change in the deep tropics and overestimates it in the subtropics (Fig. 9). These discrepancies may reflect imperfections in the surface-troposphere coupling in models, especially with respect to water vapor (Sun and Held 1996). Excessive lateral mixing between the deep tropics and

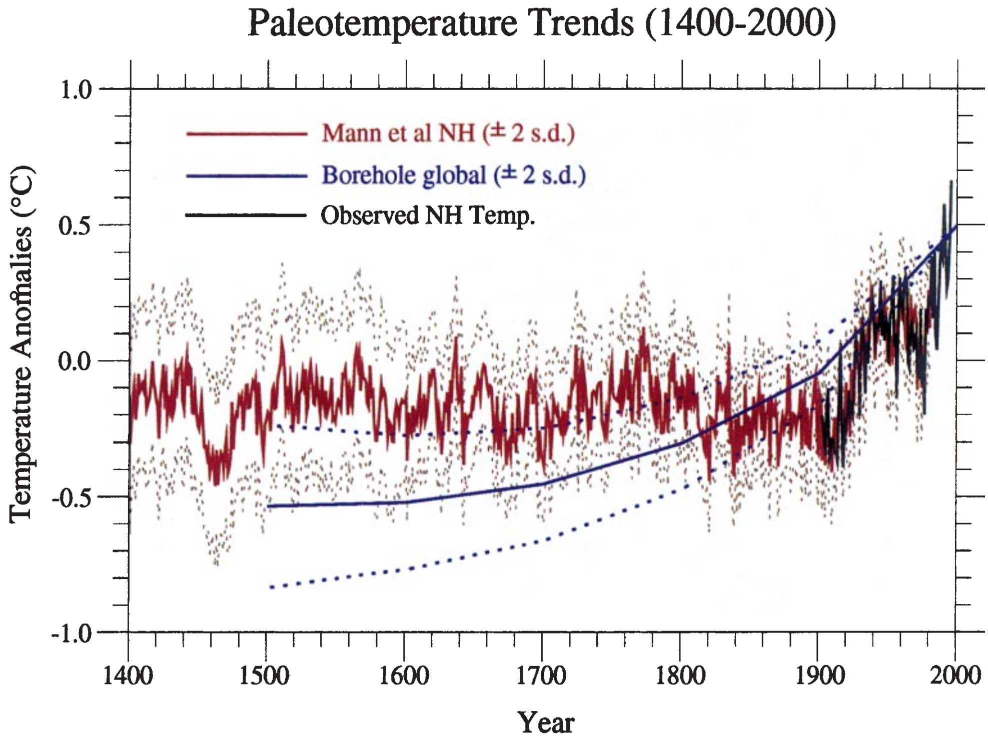

Fig. 8 Examples of two Northern Hemisphere temperature reconstructions over the last few centuries, one based on proxies with mean annual resolution from Mann et al. (1998), the other on borehole temperatures i.e., Pollack et al. (1998)

the subtropics might explain the latitudinal discrepancies (see Pierrehumbert 1998).

This discussion indicates that the relationship between observed changes in both surface and upper air fields suggest is not straightforward. Surface changes inferred from upper air variations may be precarious, and the problem carries over into models. These arguments offer independent evidence that down-projecting upper elevation data to the surface may result in misleading conclusions about the nature of surface temperature change, for the twentieth century, the Little Ice Age, and (by extension) the ice age.

4. Coral paleotemperature estimates may require re-evaluation. Given the extremely good correlations often observed between monthly geochemical measurements and observed SSTs, this may seem like a rash statement, but it is necessary to consider just how these calibrations were obtained. First, almost all the calibrations were against some local SST measurement, yet authors have drawn inferences about measurements made for a few locations to the entire tropics. Is this approach valid? We (Corwley et al. 1999, in press) maintain that there are two essential additional steps that must be taken to evaluate coral paleotemperatures: (a) the coral measurements must also be calibrated against a regional gridded field; if one cannot demonstrate high correlations to the local grid box, then extrapolations to the whole tropics are meaningless; (b) the coral temperature equations must also be validated against an independent data set from the early twentieth century.

When these steps are taken a rather surprising result is obtained (Fig. 10). For oxygen isotope records a coral that has very high monthly correlations (0.88) with the gridded data set overestimates early twentieth century cooling by a factor of about four. Preliminary assessment of some other coral records indicates similar problems (Corwley et al. 1999, in press). Although Sr/Ca estimates from the same coral agree with early twentieth century SST estimates (Crowley et al. 1999, in press), Sr/Ca measurements from a Great Barrier Reef coral do not (Alibert and McCullough 1997).

Low frequency changes in salinity may be important for explaining some of the "drift" in coral temperature estimates (Crowley et al. 1999, in press; Quinn et al. 1996; Shen et al. 1996). Although further testing of those results are necessary, the lack of validation of coral temperature calibrations cannot be ignored. One must demonstrate that corals predict the correct temperatures for the early twentieth century before drawing inferences for the whole tropics based on unvalidated spot measurements of short time series from (so far) two sites. The usual implicit assumption of stationarity in which corals fractionate elements from seawater needs also to be questioned, given the above discussion on the likelihood that, if tropical SST changes were really 5 °C less than present, ice-age corals would have been living under stressed conditions (see Fig. 6).

5. Groundwater temperature changes during the ice age do not necessarily reflect SST changes. That is, even if groundwater temperature estimates are accurate, they still may not be a 1:1 reflection of offshore temperatures. For example one groundwater site in south Texas (Stute et al. 1992) records glacial-interglacial temperature changes of about 5 °C, about 3 °C colder than indicated by CLIMAP reconstructions offshore in the Gulf of Mexico. But living in Texas has made me realize there

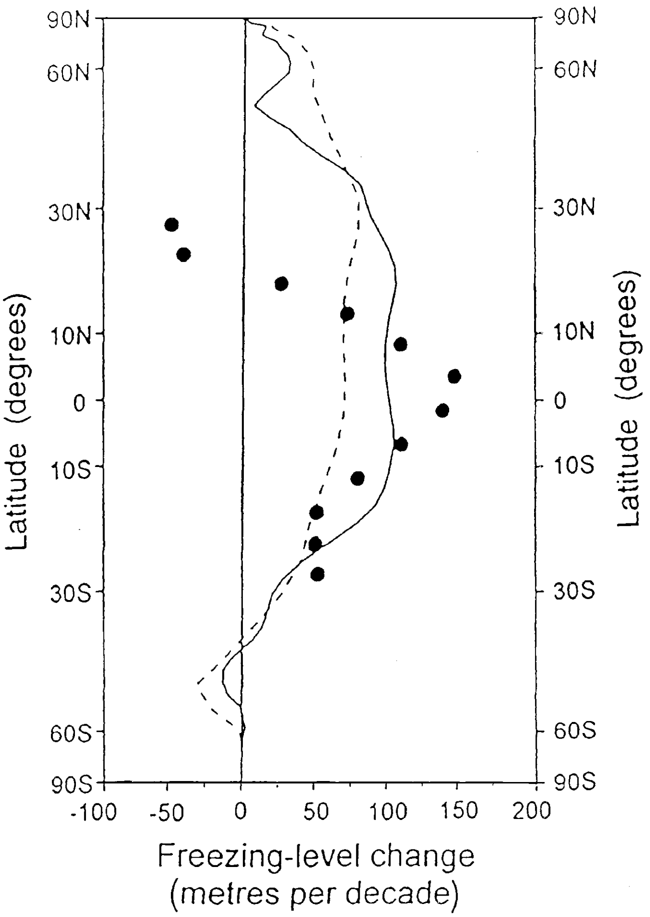

Fig. 9 Comparison of the zonal mean linear trend (m) of the computed versus observed changes in annual mean freezing-level heights in the tropics for the recent 1970–1988 warming. The model results are from an 18 y GCM simulation with the T21 (*dashed line*) and T42 (*solid line*) versions of the Hamburg GCM ECHAM2. *Dots* indicate radiosonde observations. Figure from Diaz and Graham (1996)

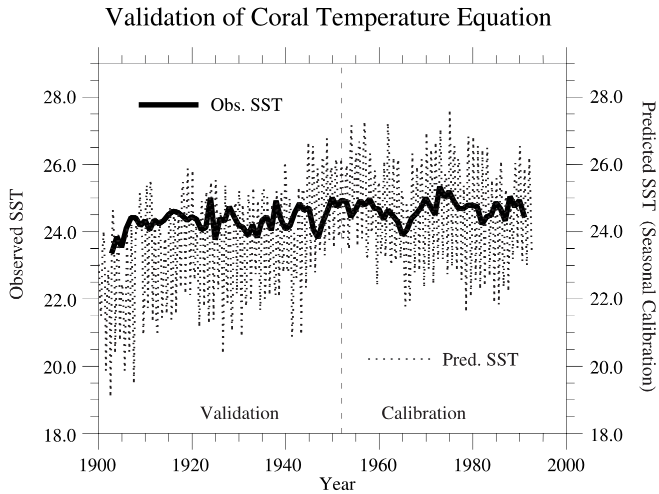

Fig. 10 Validation of a high quality coral $\delta^{18}O$ calibration against early twentieth century SSTs. The 40-year calibration interval had a $\delta^{18}O$/SST correlation of 0.88. Validation of SST calibration from the early twentieth century results in a steady drift away from observed mean annual temperatures. Routine validation exercises need to be undertaken for other $\delta^{18}O$ and Sr/Ca records to better constrain uncertainties in coral paleotemperature estimates. Modified from Crowley et al. (1999)

are sometimes quite substantial differences between temperatures on land and at sea, especially in winter, when the warmer waters are downstream of the cold continental air. It is not rare to have a 20 °C temperature gradient across the state. Also the groundwater site in Texas was recharged from a more northerly region in central Texas, where mean annual temperatures are lower. Another factor to consider is that land surface and vegetation changes during the ice age may have modified any temperature signal transmitted from the ocean (Crowley and Baum 1997).

4 Some model sensitivity experiments

To address some of the points discussed, particularly with respect to groundwater estimates, we have investigated what models predict at low elevation sites on land, with CLIMAP SSTs stipulated as input boundary conditions (Crowley and Baum 1997). Experiments were conducted with the GENESIS GCM verson 1.02A (Thompson and Pollard 1995), with the LSX land surface package of Pollard and Thompson (1995). Experiments used the Peltier (1994) ice sheet reconstruction and CLIMAP SST anomalies differenced from control run SSTs. The purpose of the study was to first quantify the level of model-data agreement at low elevation sites in the tropics. These sites are in closer thermal communication with the ocean than the upland sites. Simulations employed both present vegetation for the glacial maximum and an estimate of ice age vegetation based on pollen reconstructions (Crowley 1995). Model results were differenced from land surface sites which utilized only quantitative reconstructions of proxy temperatures; most pollen studies were not used in the validation for the reasons cited already.

Results indicate that temperatures on land sometimes differ significantly from offshore temperatures, and that vegetation can further modify the signal. In particular Africa and Australia are 0.9 °C and 0.4 °C cooler than the run with modern vegetation, with glacial-interglacial changes of 3.8 °C and 3.4 °C respectively. Even in the absence of further modifications of the SST field, these numbers are not grossly different than upper air changes estimated at about 4–5 °C. The situation is different for South America, where the great reduction in tropical rainforest resulted in warmer temperatures than in the run with modern vegetation. This latter response is similar to scenarios for future Amazon deforestation (Dickinson and Kennedy 1992; McGuffie et al. 1995) and reflect the fact that in the climate models, albedo changes are overridden by changes in latent heat release from the land surface, with changes in cloudiness yielding an additional positive feedback (Crowley and Baum 1997).

Regardless of the considerable uncertainties with respect to the vegetation reconstruction and model feedbacks, this exercise demonstrates the importance of examining model predictions at the site where the data are located. The results also suggest that plausible changes in vegetation can sometimes further modify the model response. A comparison (Fig. 11b) of model predicted temperatures with quantitative lowland proxy data indicates slightly more than 50% agreement (at the 2σ level) for an admittedly small data set ($n = 12$) of proxy temperature changes between 40°N and 40°S. In this exercise the comparison took into consideration the uncertainty in the proxy data reconstruction and also the (considerably smaller) uncertainty in model-generated glacial-interglacial differences that were due to interannual variability in the model.

One of the most prominent disagreements between model and data involves Brazil, where the model is 3.0 °C warmer than the data (disagreements in northwest Europe may reflect too much sea ice in the North Atlantic, see Crowley and Baum 1997). Two additional sensitivity experiments determined that additional cooling in the equatorial Atlantic upwelling zone (Curry and Oppo 1997; Ravelo et al. 1990; Yu et al. 1996), upwind of the Brazil site, could account for an additional 0.8 °C cooling at the Brazil site (Crowley and Baum 1997), and an alternate vegetation specification an additional 0.3 °C cooling (T. Crowley, J. Adams, S. Baum unpublished results).

The results suggest that it is not possible to completely reject the CLIMAP SST reconstruction, in the sense that not all the model results disagree with observations. But the results do suggest there may be some need for modification of the CLIMAP data (along with some of the other proxy data discussed). To address this problem further the Crowley and Baum (1997) study was repeated except that CLIMAP SSTs were uniformly lowered 1 °C (Fig. 11a). Such a uniform change is less realistic than the variable regional changes that probably occurred, but given incomplete data the option is justifiable. The new simulation resulted in an almost uniform 1 °C cooling response in different regions; that is, once the land-sea mask and vegetation changes are accounted for, uniform changes in SST almost linearly map onto land. This result means that any additional uniform modifications to the CLIMAP SST field do not necessarily require additional runs and can be fairly reliably estimated. Global average temperatures decreased 1.15 °C, a result suggesting a slight amplification of the SST change in the atmosphere due to the water vapor feedback. Two new groundwater sites (Nigeria and Vietnam) were also added to the comparison data set.

There are now only two data points in the tropics disagreeing with model predictions (Fig. 11c), and these discrepancies are plausibly due to changes in dynamics not accounted for by a GCM with fixed SSTs. For example, stipulation of SSTs around the South African site are highly uncertain due to the possible absence of the Agulhas Current in the Pleistocene; other land sites

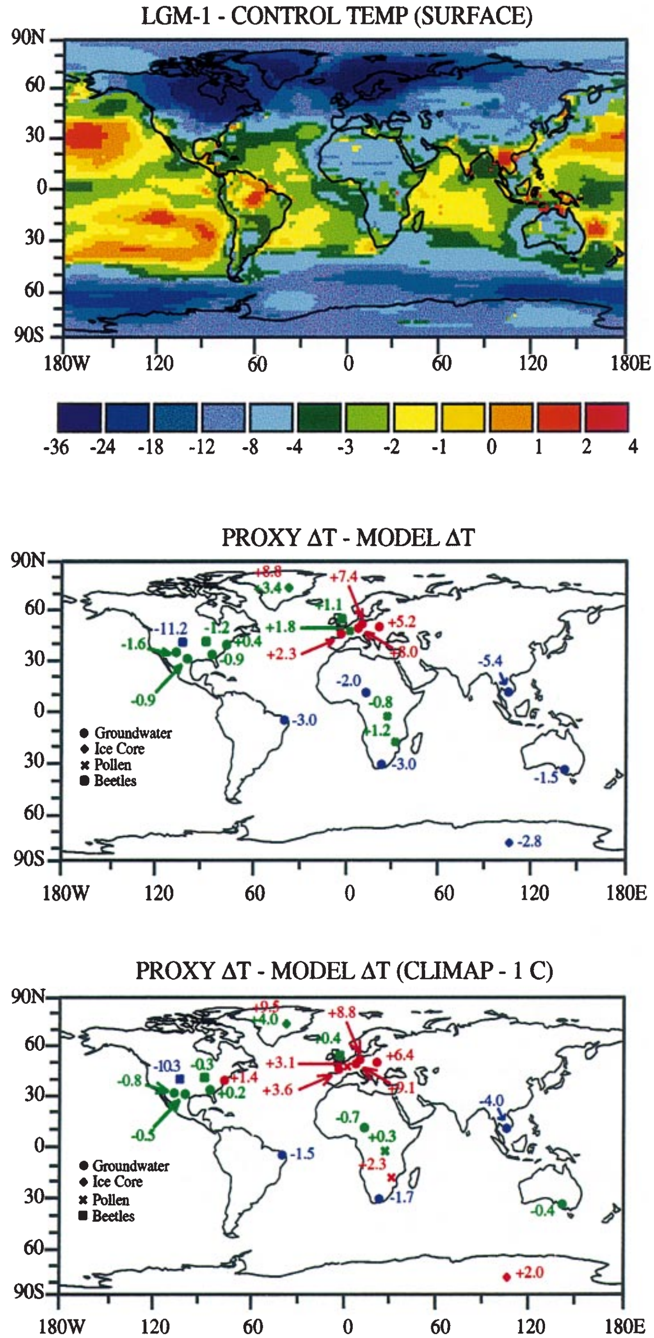

Fig. 11 (*Top*) Last glacial maximum differences in mean annual surface temperature between the ice age (CLIMAP-1) and control (see text); (*middle*) differences in mean annual surface temperature as calculated by the GENESIS GCM with CLIMAP SSTs and those determined from observations. Negative values mean that proxy data glacial–interglacial differences are greater than those generated from the model (which used climatological SSTs in the control run). *Green* indicates that the data and model agree with each other at the 2σ level; *blue* that the data are colder than the model at this level, and *red* that the data are warmer than the model at the 2σ level; (*bottom*) temperature differences between ice age model and data (same as middle panel), except that CLIMAP SSTs have been uniformly reduced 1 °C. See text for further discussion. *Top panel* from this study; *middle panel* based on results from Crowley and Baum (1997); individual data points are listed in Crowley and Baum (1997), except for new points in Nigeria (Edmunds et al. 1998) and Vietnam (Stute et al. 1997). *Bottom panel* is from the present study

nearby show larger surface temperature decreases. For the Brazil site additional local upwelling/vegetation changes could account for an additional 1 °C cooling (see earlier discussion). For the Vietnam site the CLIMAP-1 SST anomaly field (Fig. 11a) indicates a rather large cooling along east Asian waters as far south as the South China Sea (see Miao et al. 1994), but it is not clear why this anomaly does not affect land temperatures more. Overall, there may be no need to invoke larger SST changes to explain changes on land, at least for quantitative low elevation land data, once localized greater cooling is incorporated. Running models at higher resolution should also decrease land temperatures more due to greater discrimination of the land temperature elevation "increase" from a lowering of sea level. Broccoli (1999 in press) has calculated that such an effect is on average about 1.0 °C. This is not to state that larger SST changes did not occur, only that from a statistical viewpoint they may not be necessary to reconcile marine and land data in the tropics.

What about upper air results? As stated there are some reasons to question model-generated upper air changes, but we nevertheless examined the problem (Fig. 12). Glacial–interglacial differences in the freezing line of our baseline run (with "realistic" vegetation and CLIMAP SSTs) are only on the order of 200–400 m, although it is of interest that the changes in the "deforested" area of South America are much greater. This response presumably reflects the decreased convection with decreased latent heat release in the region (Crowley and Baum 1997). Although many tropical regions still have freezing line changes on the order of 400–600 m with SSTs reduced 1 °C, the additional freezing line change over South America is very close to being in line with snowline changes over the Andes (close to 800 m lowering), with convective changes potentially influencing isotopic variations reported on in Thompson et al. (1995). Similar results were obtained by Hostetler and Mix (1999). The 200–300 m average freezing line shift between the two runs for a 1 °C cooling reflects the amplification of the cooling signal with height due to decreased water vapor content in the upper atmosphere.

A final consideration involves the accuracy of surface temperature estimates derived from groundwater measurements. Although this method continues to yield impressive results, the resulting ice-age surface temperature reconstruction contains some troubling features: (a) a temperature difference of only about 3–4 °C between the deep tropics (5–6 °C) and regions just south of the great ice sheets (8–9 °C) – is this physically reasonable? Webb et al. (1997) have suggested that maintaining the present ocean heat transport during the glacial period could account for such a pattern, but I find it difficult to understand why the ocean heat transport should remain the same, especially since the ocean heat transport in different ocean basins is strongly influenced by three fundamentally different processes, the conveyor belt in the North Atlantic, the primary subtropical gyres in the Pacific, and the monsoonal system in the Indian Ocean; (b) predicted temperature changes in Germany and France of 5–7 °C seem to estimate above-freezing temperatures in some regions otherwise indicated to have frozen ground (permafrost) in the ice age (e.g., Dawson 1992). These divergent estimates are difficult to understand and suggest that there may be some need to further scrutinize groundwater temperature measurements.

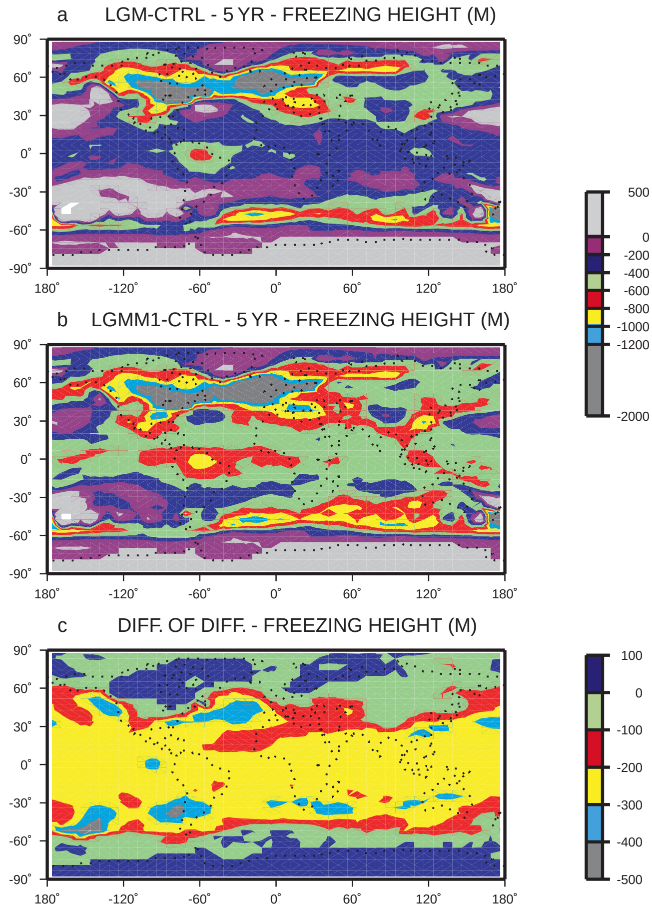

Fig. 12a–c Differences in freezing line level between control run and **a** baseline run with CLIMAP SSTs; **b** control and CLIMAP SSTs with an additional 1 °C cooling; and **c** difference between baseline SST run and run with SSTs 1 °C lower. See text for further discussion

5 Summary and discussion

To summarize, plankton data continue to support the concept that, although tropical SSTs were not as warm as CLIMAP Project (1981), changes in the tropical warm pools were still relatively modest (order 2.0–2.5 °C decreases) during the last glacial maximum. Some data, such as pollen and corals, are open to reinterpretation or more testing, while others (snowline) may not be as direct measures of SST as often assumed. Direct comparison of model results with observations indicate that about 50% of the low elevation quantitative land data in the tropics are in agreement with CLIMAP SSTs. A uniform lowering of SSTs by another 1.0 °C results in all but two points in the deep tropics now agreeing with observations. These discrepancies could either be explained by slightly greater local cooling and/or some additional level of overall cooling in the tropics (0.5 °C?).

Remaining differences between low and upper elevations on land could be accommodated by a modest (5–10%) adjustment in the lapse rate, which data from the Little Ice Age and twentieth century justify. Such changes have also been proposed based on a comprehensive reanalysis of terrestrial data (Farrera et al. 1999 in press). Model-data differences in estimated surface and mid-troposphere temperature changes could as well reflect inadequacies in the convective adjustment scheme of GCMs rather than the input tropical SST field. These arguments therefore suggest that there may be no need to invoke a 5 °C tropical SST cooling to explain land data. The proposal would result in tropical SSTs warm enough to support tropical marine biota (including corals) but require recalibration of coral SST proxies, for reasons discussed in the text.

How can this conclusion be reconciled with recent coupled model results indicating that tropical SSTs may have decreased 5 °C (Bush and Philander 1998b)? This latter response occurred primarily as a result of increased cooling due to decreased CO_2 levels. This same model also predicts about a 5 °C SST increase for warm time periods (Bush and Philander 1998a; Manabe and Bryan 1985) – a response not observed in the geologic record (Crowley and Zachos 1999 in press). So, rather than supporting some of the questionable conclusions about 5 °C cooling in the tropics, the reason for the model cooling may simply reflect a too strong positive feedback in the tropics (in other words the clouds in the real world may have more of a negative feedback than they do in the model). Thus this model result should not be construed to indicate that there is now agreement between models and observations for a 5° C tropical cooling. Other coupled model runs (Ganopolski et al. 1998; Weaver et al. 1998) suggest that tropical cooling of 2–3 °C are consistent with radiative forcing changes for the last glacial maximum.

What are the implications of this proposed resolution for climate sensitivity? Given the continuing uncertainties in paleo-SSTs and ice-age boundary conditions, it is probably not possible to estimate sensitivities more precisely than as "low", "middle" or "high". The global average surface temperature decrease for the CLIMAP-1 run is 5.3 °C. A 4–5 °C cooling for the warm pool would lower this value to 7 °C or more and be broadly consistent with a high-end sensitivity around 4.5 °C (Crowley 1994). A rough estimate of the sensitivity decrease would therefore be about 25–30% less than large warm pool SST changes. CLIMAP SSTs are generally compatible with a model sensitivity of about 2.0 °C for a doubling of CO_2 (Hoffert and Covey 1992; Hyde et al. 1989). Thus the "modified warm pool" scenario proposed herein would be consistent with a sensitivity of about 3.0 °C. This conclusion agrees with one derived by Broccoli (2000 in press) using an alternative approach but is less than the "high-end" ice-age sensitivities of Hansen et al. (1993); Hewitt and Mitchell (1997).

The proposed resolution to the ice age tropical SST problem also has implications for theories of stability of tropical SSTs. Accurately predicting the future course of warm pool SSTs has substantial implications for estimates of greenhouse gas climate sensitivity. There has been some discussion about the possibility of a tropical thermostat (Ramanathan and Collins 1991). El Nino studies clearly demonstrate that changes in Pacific tropical SSTs have a planetary scale impact. The same may hold true on the greenhouse scale, for Meehl and Washington (1996) have demonstrated significant differences in regional responses that depend on whether warm pool temperatures are capable of changing. Obviously any 5 °C cooling would seriously undermine the validity of any argument about the stability of tropical SSTs.

Most suggested CLIMAP modifications involve substantial changes in limited areas such as eastern boundary currents and equatorial Atlantic and Pacific upwelling zones (see Mix et al. 1999). However, mean annual SST changes in the western Pacific warm pool (see earlier), far removed from any influence by ice sheets, are estimated to be only 1.1 °C by CLIMAP, or 2.1–2.6 °C with the adjustment proposed herein. This modified range is similar to tropical SST changes in reconstructions of time periods warmer than present Crowley and Zachos (2000). If the proposed ice age resolution is substantiated, then there is a certain symmetry with respect to the sensitivity of the warm pool response, with both warmer and colder time periods providing evidence for a "modified thermostat" feedback mechanism which allows SSTs to fluctuate some (±2–3 °C) but not greatly (±5–6 °C).

The climate of the last glacial maximum continues to fascinate in terms of the wealth of information that can be extracted from it. Future work may well modify the views stated herein; a very desirable goal is to re-do the CLIMAP SST reconstruction with the nearly two decades of additional data and improved analysis techniques. But there now appears to be at least some glimmering of a hope for reconciling estimates from data and models, with conclusions having significant implications for climate sensitivity, stability of the tropical Pacific warm pool, and the ecology of tropical biota.

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