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Dynamical and observational constraints on tropical Pacific sea surface temperatures at the last glacial maximum

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Abstract. Asynchronously coupled atmosphere and ocean general circulation model simulations are used to examine the consequences of changes in the west/east sea-surface temperature (SST) gradient across the equatorial Pacific at the last glacial maximum (LGM). Simulations forced by the CLIMAP SST for the LGM, where the west/east SST gradient across the Pacific is reduced compared to present, produce a reduction in the strength of the trade winds and a decrease in the west/east slope of the equatorial thermocline that is incompatible with thermocline depths newly inferred from foraminiferal assemblages. Stronger-than-present trade winds, and a more realistic simulation of the thermocline slope, are produced when eastern Pacific SSTs are 2°C cooler than western Pacific SSTs. Our study highlights the importance of spatial heterogeneity in tropical SSTs in determining key features of the glacial climate.

The first synthesis of sea-surface temperatures (SSTs) at the last glacial maximum (LGM: ca 21,000 calendar yr B.P.), made by the CLIMAP Project (CLIMAP, 1981) indicated that the average cooling of the tropics was ca 2°C. Climate simulations in which the SSTs were prescribed from the CLIMAP data set were unable to reproduce the magnitude of the cooling inferred from the depression of snowlines on tropical mountains (Rind and Peteet, 1985). Several lines of evidence now suggest that the tropical SST cooling might have been larger than shown by CLIMAP. Studies based on noble gas palaeothermometry and Sr/Ca ratios in corals have shown cooling of ~5-6°C in several regions (e.g. Guilderson et al., 1994; Stute M. et al., 1995). However, new syntheses of both terrestrial evidence for tropical lowland cooling (Farrera et al., 1999) and alkenone-estimates of SST changes in the tropical Indian Ocean (Bard et al., 1997) limit the plausible magnitude of cooling in some tropical regions to less than 3°C.

One key aspect of the CLIMAP synthesis that has been overlooked in the current debate about tropical cooling is the strong geographical patterning of SST anomalies. In the tropical Pacific, the SST anomaly shows a distinct pattern with a reduced west/east SST gradient relative to present. The SST cooling is at the order of 2°C in the western Pacific warm pool, but smaller in the eastern tropical Pacific (Fig.1). The CLIMAP SSTs in the western Pacific are consistent with terrestrial evidence from New Guinea and Indonesia for relatively little change (<2°C) in temperature at low elevations (Farrea et al., 1999). In contrast, the CLIMAP SST in the eastern tropical Pacific, which shows little cooling (or even warming in the southern eastern tropical Pacific), seems to be inconsistent with other observations. Recent analysis of radiolarian assemblages (Pisias and Mix, 1997) indicates that the SSTs in the eastern equatorial Pacific were 3 to

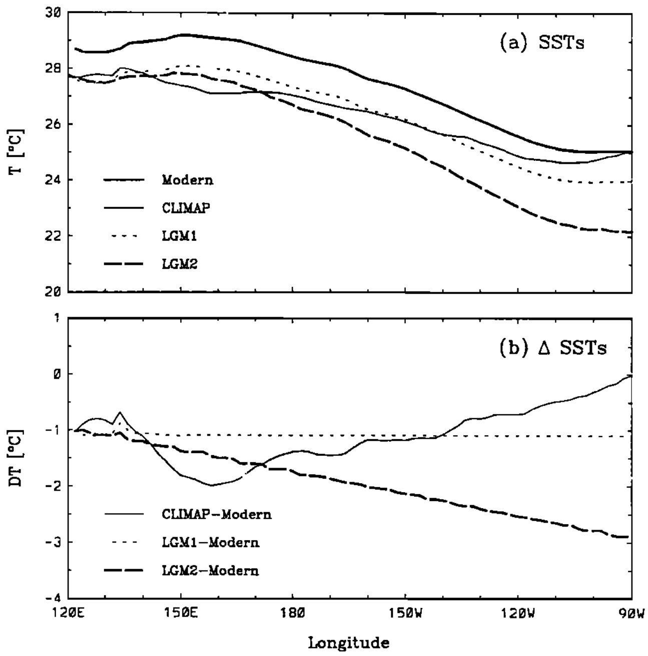

Figure 1: Annual mean SST (a) and SST anomaly (relative to present) (b) averaged between 10°S and 10°N in the Pacific. The CLIMAP SST and SST change are in thin solid lines. Levitus (1982) SST is used as the present SST (heavy solid line in (a)). Also plotted are the SST and SST anomalies for the sensitivity experiments of LGM1 (dot) and LGM2 (heavy dash) which differ from the CLIMAP run only in the SST within 10° of the equator.

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5°C lower than present; terrestrial evidence from equatorial South America also indicates a sea-level temperature 4-6°C colder than today (Farrera et al., 1999). Thus, the west/east SST gradient in CLIMAP seems to be inconsistent with recent data from the eastern Pacific. Furthermore, the reduced west/east SST gradient is dynamically inconsistent with evidence of stronger trade winds off South America and over the equatorial Pacific at the LGM (Chuey et al., 1987).

Here, we further ask whether the CLIMAP reconstruction is dynamically consistent with recent observation of the changes in the vertical structure of the tropical ocean at the LGM. Reconstructions of changes in the depth of the thermocline in the tropical Pacific based on changes in foraminiferal assemblages show a coherent spatial patterning: the thermocline was ca 20m deeper than it is today in the central Pacific (ca 150°E-150°W) but ca 10m shallower than today in the eastern Pacific (150°W-110°W), implying a steeper thermocline slope (Andreasen and Ravelo, 1997; Trend, 1999). An asynchronously coupled atmosphere-ocean model will be used to examine the dynamic consistency of the CLIMAP SST and the equatorial thermocline. The atmospheric model is the NCAR Genesis2 at T31 resolution (Thompson and Pollard, 1997). The extent and height of the LGM ice sheets (Peltier, 1994) and insolation (Berger, 1978) were prescribed, and the atmospheric CO_2 content was set to 345 ppmv in the control and 200 ppmv in the LGM simulations (Barnola et al., 1987). The ocean model is the Miami Isopycnal Model (Bleck et al., 1992), with a horizontal resolution of 2° x 2° and 12 vertical layers, and a model domain of the Pacific north of 40°S. The models were asynchronously coupled, such that the OGCM was driven by the output derived from the AGCM, following the equilibrium asynchronous coupling procedure described by Liu et a. (1999). In addition to the modern control simulation, we ran three experiments (CLIMAP, LGM1, LGM2).

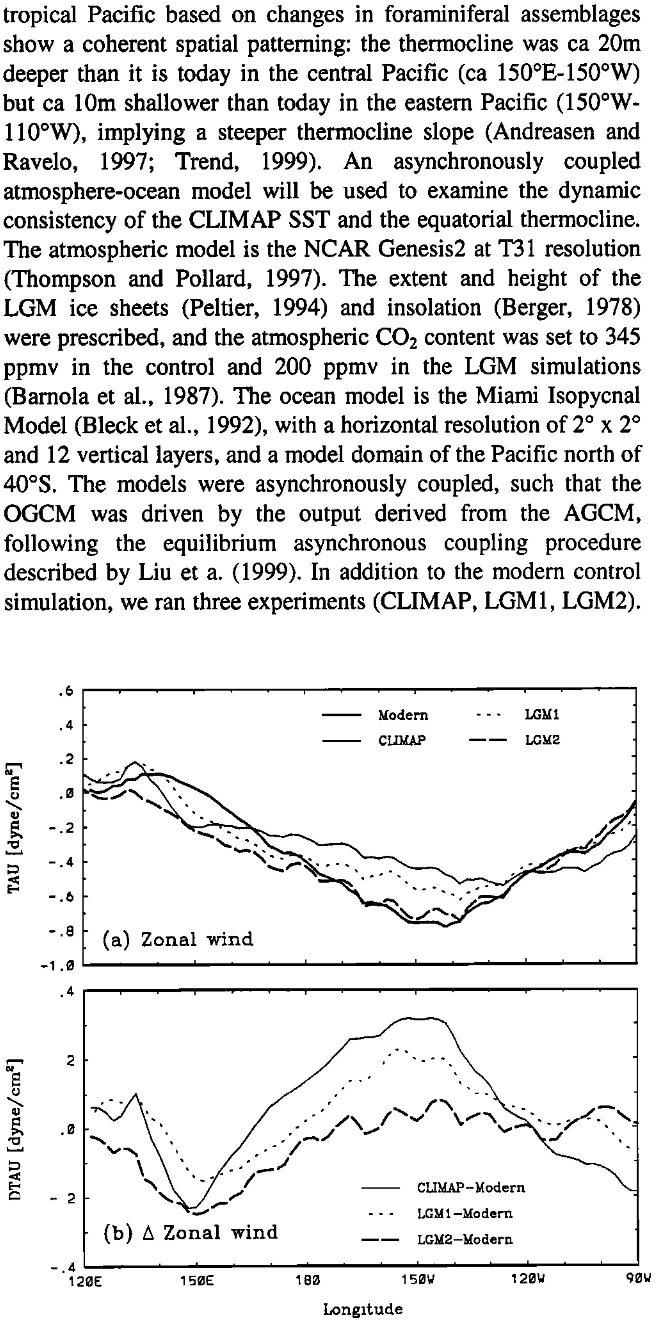

Figure 2: Along equator zonal wind stress (a) and zonal wind stress anomalies (b) from the AGCM experiments of CLIMAP (thin solid), LGM1 (dot) and LGM2 (heavy dash). The wind stress anomaly in (b) is derived relative to a modern AGCM experiment forced by the Levitus (29) SST. The wind stress is averaged between 5°S and 5°N.

In each experiment, the AGCM was first forced by the SST field (Fig.1), and the AGCM surface forcing was then applied to force the OGCM.

We will show that the reduced west/east SST contrast across the equatorial Pacific in CLIMAP SST is dynamically inconsistent with the enhanced thermocline slope inferred from recent observations. The dynamic principle is straightforward. A reduced west/east SST contrast weakens the surface trade winds due to a weaker Walker circulation. The weaker trades generate a smaller west/east oceanic pressure gradient and therefore decrease the thermocline slope, contradicting the increased thermocline slope inferred from proxy data (Andreasen and Ravelo, 1997; Trend, 1999). In our coupled simulation (CLIMAP) that is forced by the CLIMAP SST field, the strength of the trade winds is reduced by > 30% over much of the central Pacific (Fig 2a, 2b) because of the reduced west/east SST contrast. The reduction of trade winds at the LGM is a robust feature of AGCMs, shown e.g. by all PMIP model experiments (Pinot et al., 1999). This weaker trade wind reduces the slope of the equatorial thermocline (Fig. 3). The modern equatorial thermocline is deeper in the central-western Pacific than in the eastern Pacific due to the westward trades. In the CLIMAP simulation, the thermocline is about 20m shallower than today in the central Pacific, and slightly deeper than today in the far eastern Pacific (Fig. 3), resulting in a decreased thermocline slope that contradicts the LGM reconstruction.

We performed two LGM sensitivity experiments in which the equatorial Pacific SSTs within 10° of the equator were modified from the CLIMAP SSTs. In LGM1 we eliminated the anomalous west/east gradient in CLIMAP in the equatorial Pacific by assuming that the SST anomaly in the equatorial Pacific is zonally uniform with a magnitude of ca 1°C (Fig.1). In LGM2, we reversed the anomalous west/east gradient: the SSTs were 1°C colder than present in the western Pacific, which is similar to the CLIMAP SST cooling there, but 3°C colder than present (2°C to 3°C colder than CLIMAP) in the eastern Pacific (Fig.1). The weakening of the westward trade wind in the central equatorial Pacific is less severe in the LGM1 than in the CLIMAP simulation (Fig.2). In LGM2, the trade wind is strengthened (rather than weakened) in the central Pacific (Fig.2). In LGM1, the smaller reduction in the strength of the trade winds makes the thermocline slightly shallower in the eastern Pacific, and thus slightly enhances the thermocline slope relative to the CLIMAP run (Fig 3). In LGM2, however, the enhanced trade winds lead to a steeper equatorial thermocline slope: the thermocline is ca 10-20m deeper than today in the central and western Pacific. The simulated change in the thermocline depth in the central Pacific is in good agreement with the reconstructed change of thermocline depth. Thus, a match with the observations of the LGM thermocline is only produced when the west/east SST contrast is intensified, as in LGM2.

The thermocline slope in the eastern Pacific in LGM2 is not as steep as shown by observations. The data indicate a shallower thermocline in the eastern Pacific (120-130°W), while the LGM2 simulation produces no change or a slightly deeper thermocline. This discrepancy may reflect uncertainties associated with the reconstructions in the eastern Pacific (Fig 3) where modern analogs have lower similarities, and the reconstructed estimates of thermocline depth have a wider spread than elsewhere in the Pacific (Andreasen and Ravelo, 1997; Trend, 1999). There also seems to be inconsistency in the reconstruction of marine biological productivity in that region (Loubere, 1999). It is also likely that the simulated thermocline slope is less steep than

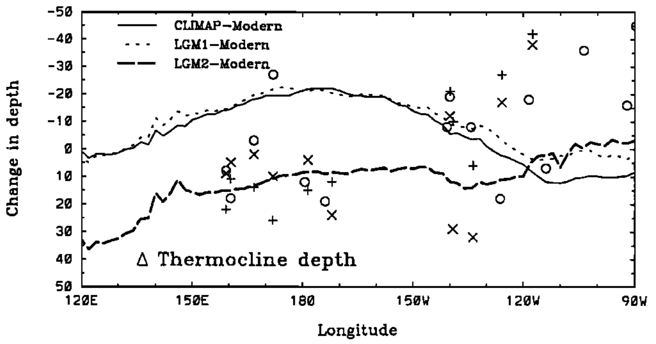

Figure 3: LGM thermocline depth anomalies along the equator. Crosses (modern analog method from (13)), circles (modern analog method from (14)) and pluses (Imbrie-Kipp method from (13)) are the estimated LGM depth anomaly (of cores between 6°S and 5°N) for the 18°C isotherm. The curves represent the model 20°C isotherm depth anomalies averaged between 5°S and 5°N (relative to the modern control run) for the OGCM experiments of CLIMAP (thin solid), LGM1 (dot) and LGM2 (heavy dash). The 20°C model isotherm corresponds better to the 18°C isotherm in observation, because our model thermocline is more diffusive than the observation.

shown by the data because the prescribed change in eastern Pacific SSTs in LGM2 was conservative. Marine (Pisias and Mix, 1997) and terrestrial (Farrera et al., 1999) estimates indicate that the eastern equatorial Pacific was 3-6°C colder than present; the prescribed change in eastern Pacific SSTs was <3°C. Colder SSTs in the eastern, and especially the southeastern, equatorial Pacific, by increasing the northwestward pressure gradient more than in LGM2, would intensify the northwestward trade winds in the eastern equatorial Pacific, causing a further shallowing of the thermocline in the eastern Pacific, in better agreement with the observations.

The west/east contrast in SSTs, with warm conditions in the western Pacific and cooler conditions in the eastern Pacific, is an important fingerprint of the dynamics of the tropical climate at the LGM. Without this contrast it is impossible to generate the reconstructed Pacific subsurface oceanic structure at the LGM. Thus, this fingerprint permits us to evaluate the realism of existing simulations of the LGM climate made in the Palaeoclimate Modelling Intercomparison Project (PMIP). The PMIP simulations with mixed-layer ocean models tend to produce a uniform tropical cooling (Pinot et al., 1999), which are inconsistent with the terrestrial evidence for changes in temperature at sea level (Farrera et al., 1999). These models also produce changes in the strength of the trade winds which, according to our simulations, would cause changes in oceanic structure that are incompatible with reconstructions of the change in thermocline slope between the LGM and present.

We have shown that SSTs in the eastern Pacific must have been at least 2-3°C colder than shown in the CLIMAP data set, and that a cooling of >3°C would likely produce a better fit to various observations. This is consistent with a recent independent study (Hostetler and Mix, 1999). Furthermore, we have demonstrated that the west/east SST contrast in the equatorial Pacific is the primary driving force for the equatorial trades, and an important fingerprint of the dynamics of the LGM tropical climate. The west/east SST gradient in the tropical Pacific may also be an important feature of simulations of future climates (e.g. Kuntson and Manabe, 1995). Our analyses suggest that the identification and investigation of dynamically consistent characteristic patterns, through combining spatially-distributed observations from multiple (terrestrial and oceanic) data sources with general circulation model experiments, can provide a much more comprehensive understanding of the climates of glacial and interglacial periods and a better appreciation of the modes of operation of the climate system.

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