Scenarios regarding the lead of equatorial sea surface temperature over global ice volume

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[1] Recent proxy evidences indicate that the equatorial sea surface temperature (SST) may have led global ice volume by ∼3 kyr during the late Pleistocene glacial cycles. Given the short timescales of equatorial dynamics, equatorial climate variability is characterized by a timescale of no more than a few years. It would seem somewhat surprising therefore that the equatorial ocean and atmosphere can determine and lead the long-timescale 100 kyr glacial cycles. Two scenarios are presented according to which such a lead may be observed even when the equatorial ocean and atmosphere are not necessarily responsible for leading the glacial cycles (they may still act as a strong amplifier). First, it is shown that if the plankton-based proxy reflects the warm season temperature rather than an annual temperature, it may lead the global temperature, although the dynamics of the glacial cycles may still be dominated by the Northern Hemisphere ice sheets. It is noted that a present-day seasonal bias of the equatorial proxy record is still inconclusive, and the possibility of a proxy bias only during glacial times is considered as well. A second scenario is suggested in which global sea level rises before equatorial SST, yet the later evolution of factors such as the atmospheric CO_2 and equatorial SST is faster and takes the lead over global ice volume. If the initial rise of sea level is masked by a sufficiently large proxy noise (because of instrumental and natural noise), it may not be seen and the lead may be attributed to the equatorial SST and CO_2.

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1. Introduction

[2] Given that the majority of changes in ice volume during the Pleistocene ice ages occurred in the Northern Hemisphere (NH) ice sheets [e.g., *CLIMAP-Project*, 1976; *CLIMAP Project Members*, 1981; *Peltier*, 1994; *Clark and Pollard*, 1998; *Mix et al.*, 2001], most proposed mechanisms suggest that climate changes in the NH lead glacial oscillations. However, recent proxy observations from equatorial sites indicate a possible lead of the equatorial ocean during glacial cycles, especially during terminations [e.g., *Koutavas et al.*, 2002; *Lea et al.*, 2000; *Lea*, 2002; *Nürnberg et al.*, 2000; *Schneider et al.*, 1999; *Pisias and Mix*, 1997; *Visser et al.*, 2003]. Some off equatorial land sites also indicate such a lead [e.g., *Seltzer et al.*, 2002a; *Smith et al.*, 2005], although see *Clark* [2002] and *Seltzer et al.* [2002b]. These observations indicate that the equatorial ocean and atmosphere may lead the glacial cycle dynamics and that the NH ice sheets are merely driven from the equator [*Cane*, 1998].

[3] The equatorial ocean and atmosphere (roughly 5°S to 5°N, referred to as "the equator" below) are clearly major players in global climate dynamics. However, equatorial timescales (of ocean wave propagation, thermocline adjustment, atmospheric response times, etc.) are a few months to a few years at the most. For this reason, extratropical decadal processes are often invoked to explain decadal modulations in the El Niño–Southern Oscillation (ENSO) variability [*Gu and Philander*, 1997]. It therefore seems surprising that the equatorial SST would spontaneously go into interglacial conditions because of purely equatorial dynamics after tens of thousands of years of glacial conditions, and start the global deglaciation process.

[4] It is possible that the equatorial SST only responds to precession forcing, and affects the NH ice sheets via teleconnection mechanisms. In this case one must assume that the ice sheets do not respond to the remote equatorial forcing for several precession cycles, until they are large and "ready for a collapse." However, what internal ice sheet instability mechanism may be responsible for such a collapse is not known nor understood at this time; it therefore remains to be shown how an equatorial influence can be instrumental in ice sheet collapse. In addition, an equatorial lead is expected to spread rapidly to the global ocean-atmosphere system via atmospheric teleconnections [*Cane*, 1998], and it is not clear how the climate system can support a lead of the equatorial Pacific alone over global ice volume.

[5] The objective of this note is to examine the possibility that the observed equatorial temperature lead may not be an indication that the equator is the cause of glacial terminations. Specifically, we examine two scenarios in which this

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lead is due to (1) a seasonal bias of the proxy record or (2) a noise masking early leads of ice volume over equatorial SST.

[6] Studies using sediment traps find no conclusive evidence for a strong preferential seasonal growth of the relevant plankton in spite of much work on the subject [e.g., *Bijma et al.*, 1990; *Dekens et al.*, 2002; *Kawahata et al.*, 2002; *Koutavas and Lynch-Stieglitz*, 2003; *Lea et al.*, 2000; *Nürnberg et al.*, 2000; *Stott et al.*, 2002; *Thunell et al.*, 1983; *Troelstra and Kroon*, 1989]. Our study is therefore necessarily of a suggestive nature. The equatorial seasonal bias may not necessarily be due to seasonal temperature variations, which are not very strong at the equator. It may be related to seasonal upwelling and variations in nutrient supply; the upwelling equatorial season is currently during September rather than during the warm season (March–April), but the season of the upwelling during glacial times is not well constrained. Our approach is similar to that of *Gildor and Ghil* [2002], who suggested that the observed lead of Antarctic temperature and atmospheric CO_2 concentration may be related to the seasonal bias in precipitation (for a related suggestion see also *Huybers and Wunsch* [2003]).

[7] We attempt here to account for the lead of equatorial SST over ice volume, even though both the existence of such a lead and its magnitude are uncertain. There are issues with the way such leads are calculated [e.g., *Alley et al.*, 2002]; the isotopic proxies for ice volume reflect both ice volume and local temperature; there may be a delay of up to a few thousands years between the changes in global ice volume and their reflection in the global ocean water isotopic signal; timescale uncertainties make the comparison of different proxies from different sources difficult. Finally, the cross-correlation technique that is sometimes used to quantify lags may not work well if such lags occur mostly during terminations or only for specific Milankovitch frequency bands. It seems, in fact, that some near-equatorial sites show no lead over the NH, e.g., the South China Sea [*Kienast et al.*, 2001] or the western tropical Atlantic [*Lea et al.*, 2003].

[8] The present-day equatorial Pacific seasonal cycle, with the March–April warm season and the September–October cold season, seems to be due to the asymmetric geometry of the continents around the equator [*Tianming and Philander*, 1995, 1997], and is assumed here to occur at the same calendar months during glacial periods. However, there may be significant effects on the equatorial seasonal cycle because of the large ice sheets over north America in glacial times which modify the large-scale landmass topography. The lead of local temperature over global ice volume has been deduced from proxy data for different locations, some of which are characterized by different seasonal cycles. This may serve as an evidence against our seasonal bias scenarios. As present-day seasonality is very weak in regions such as the western Pacific warm pool, we also consider here a seasonal proxy bias only during cold glacial periods. This allows for the possibility of warm water planktonic species having more difficulties tolerating the colder water during glacial times, and thus displaying a stronger sensitivity to the seasonal cycle then.

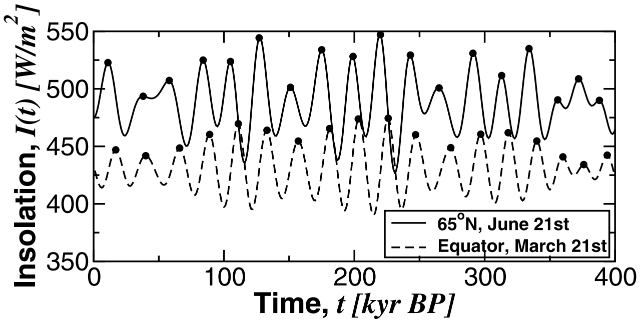

Figure 1. Insolation time series at 65°N for 21 June (longitude measured from the vernal equinox is λ = 90°) and at the equator for 21 March (the vernal equinox, λ = 0°) [*Laskar*, 1990]. Note that the 21 March insolation (warm season in the equatorial Pacific) leads the insolation of 21 June (Northern Hemisphere (NH) summer solstice) at 65°N by ~5 kyr.

[9] We next briefly discuss the lead/lag in maximum insolation at different dates in the annual cycle (section 2). Then (section 3) we visualize our argument by presenting two simple specific numerical examples of an equatorial lead in idealized model simulations where it is clear that the equator does not drive the glacial cycle. We then add artificial noise to sea level and CO_2 data, to demonstrate how an early rise of sea level may be masked by proxy noise giving the impression that CO_2 (and possibly equatorial SST) rises before sea level during glacial terminations. We conclude in section 5.

2. Leads and Lags in Insolation

[10] It is a well known property of the Milankovitch forcing that the maximum insolation in any particular month (e.g., June) may occur thousands of years before or after maximum insolation occurs in some other month (e.g., March) [e.g., *Gildor and Ghil*, 2002; *McElroy*, 2002; *Clemens and Prell*, 2003].

[11] The time lag between insolation maxima at different dates is approximately $\Delta t \approx (20\ \text{kyr})\Delta\lambda/2\pi$, where the date is given by the longitude λ of the Earth orbit around the Sun, measured from the vernal equinox, 21 March; for example, 21 September corresponds to $\lambda = \pi = 180°$. The time lag between insolation at different dates (longitudes λ) increases as the dates are further apart, up to a maximum lag (or lead) of Δt = 10 kyr obtained for $\Delta\lambda = \pi = 180°$ which corresponds to a 6 months separation.

[12] Figure 1 shows the 65°N 21 June insolation (λ = 90°) which is associated via the Milankovitch hypothesis [*Milankovitch*, 1941] with changes in ice volume. Also shown is the equatorial insolation of 21 March (λ = 0°), time of the warm season at the equator. It is clear that the equatorial insolation (in particular its maxima or minima) leads that of 65°N insolation by about 5 kyr. Thus, if glacial climate is strongly linked to 65°N 21 June insolation, one expects the equatorial warm season (March–April) temperature, which is influenced by the March insolation, to lead

global temperature by several thousands years. Therefore, if planktonic proxy records indeed reflect the warm season temperature, they may seem to lead global ice volume. We now move to a more detailed examination of this idea using a simple analysis based on SPECMAP δ^{18}O data [*Imbrie et al.*, 1984], which is orbitally tuned to the precession and obliquity and correlates well with the 65°N summer insolation.

3. Equatorial Lead: A Specific Example

[13] Start by considering a highly idealized way of calculating global and equatorial temperatures incorporating a warm season bias. We emphasize in the strongest terms that the calculation below is not meant to be a correct physical model of the glacial cycles, nor of the equatorial SST. Its only purpose is to help visualize the effect of a proxy bias on an observed equatorial lead under scenarios which are somewhat more elaborated than can be seen directly from the insolation curves of Figure 1.

[14] We crudely assume that we can write

$$T = A\delta^{18}O + B, \tag{1}$$

where δ^{18}O is the SPECMAP reconstruction, and the temperature T represents the NH temperature signal caused by NH ice sheet and albedo changes. T is referred to below as the "averaged Northern Hemisphere temperature" to emphasize that it is determined by NH processes. It is well known [e.g., *Schrag et al.*, 1996] that the δ^{18}O record is a mix of temperature and ice volume effects, and that one cannot use relations such as the above in order to accurately estimate a temperature time series from this isotopic record. We choose $A = -2.29$°C, $B = 5.61$°C to obtain a reasonable "temperature" record.

[15] Now, the average temperature T, representing the NH glacial cycles calculated via (1), affects the equatorial SST, through the effects of T on the deep water that sinks in the North Atlantic and upwells at the equator, or via atmospheric teleconnections. The SST at the equator, T_e, is therefore assumed to be influenced by local insolation and by the NH temperature, T, and is written as a weighted sum of these two factors,

$$T_e = aI_s + bT + c, \tag{2}$$

where $a = 0.055$ m^2°K/W, $b = 0.73$ and $c = 151$°K. I_s is the Milankovitch forcing at the equator for a certain longitude (date) (following *Berger and Loutre* [1991]). In order to test the effect of a warm season bias we will take below I_s to be the warm season Milankovitch radiation at the equator. Our equatorial SST equation ignores the possibly dominant effects of CO_2 [*Lea*, 2004] as well as the dynamical thermostat effects due to a coupled wind-thermocline adjustment [*Clement et al.*, 1996; *Bush and Philander*, 1998] (see also *Cane et al.* [1997] and *Mann et al.* [2005]).

[16] The averaged NH temperature T and the equatorial SST, T_e, are depicted in Figure 2a. We used the 21 April (λ = 30°) insolation as the equatorial Pacific warm season solar forcing I_s in (2). Both temperatures exhibit similar patterns of glacial-interglacial oscillations, with the precession oscillations of ~20 kyr modulating the ~100 kyr oscillations. The main result here is that times of minimum temperature (glacial maxima) at the equator lead the NH temperature terminations by several thousand years. This lead does not indicate that the terminations of the ice ages in this model are initiated at the equator, as the NH temperature in our analysis cannot be influenced by the equatorial temperature by construction.

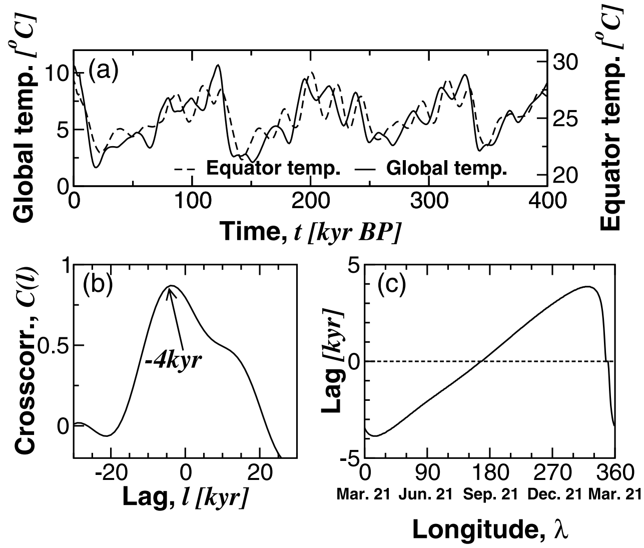

Figure 2. (a) Model-derived NH temperature-like time series (solid line, equation (1)) and equatorial temperature (dashed line, equation (2)) of 21 April. The equatorial temperature leads the NH temperature, although the NH model temperature is not affected by the equatorial model temperature by construction. (b) Cross correlation between the equatorial and NH temperature time series shown in Figure 2a. The maximum cross correlation indicates an ≈4 kyr equatorial lead. (c) Lag in kiloyears at which the maximum cross correlation occurs for model runs using different dates of equatorial insolation forcing in (2).

[17] A cross-correlation analysis between the averaged NH temperature, T, and the equatorial SST, T_e (Figure 2b), similar to that used by *Lea et al.* [2000], shows a maximal cross correlation, of 0.87 for a lag of ≈−4 kyr, meaning that the equatorial warm season SST statistically leads the NH temperature by ≈4 kyr.

[18] Figure 2c shows the lag between the NH temperature and the equatorial temperature as function of time during the year at which the equatorial insolation forcing is used. Figure 2c indicates that between March and August there is an apparent equatorial lead of up to 4 kyr.

[19] Figure 2c shows a sharp transition from a maximum lag of ≈4 kyr at February to a maximal lead of ≈4 kyr during March–April. This transition is a consequence of the limitations of the cross correlation method used here to quantify the lag. Consider, for example, two sine functions that have the same period but with variable specified phase difference. Then the lag between such two functions calculated via the cross correlation increases linearly with the

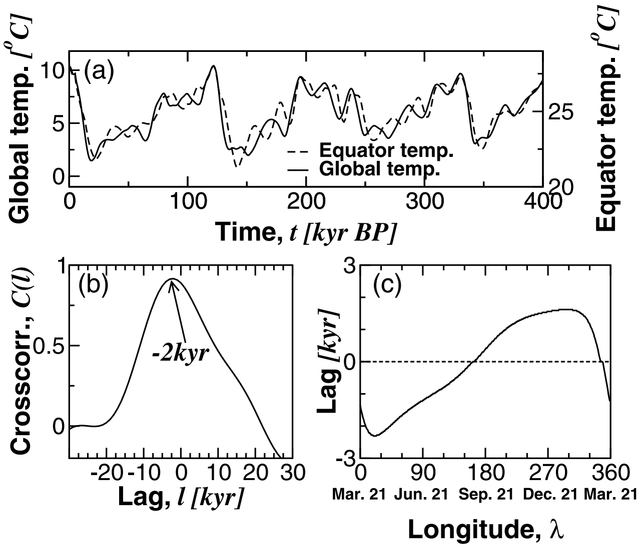

Figure 3. Same as Figure 2 but with the averaging procedure of equations (3) and (4) for w = 180. Note that estimated phase lag using the cross-correlation function is more moderate yet occurs for all but warmest periods.

specified phase difference. However, when the relative phase becomes larger than the half the period, the calculated lag sharply turns into a lead, resembling the sharp transition shown in Figure 2c.

[20] Consider now a scenario in which the plankton-based proxy record is biased toward the warm season only during glacial conditions. This is where our simple model calculation is able to add to the information in the insolation time series of Figure 1. Suppose the proxy equatorial temperature, T_e^*, reflects a temporal average of the actual equatorial temperature T_e over the warm season during glacial times and over the entire year during interglacial times. This may be represented mathematically as

$$T_e^* = \frac{1}{\sqrt{2\pi}\sigma(T)} \int_0^{2\pi} \exp\left(\frac{-(\lambda - \lambda')^2}{2\sigma(T)^2}\right) T_e d\lambda', \qquad (3)$$

where λ represents the date within the annual cycle, T is the NH temperature from (1), and T_e is the equatorial temperature from (2). The Gaussian averaging width $\sigma(T)$ is given by

$$\sigma(T) = 2 + w\left(\frac{T - T_{\min}}{T_{\max} - T_{\min}}\right)^2, \qquad (4)$$

where $T_{\max}$ = 11°C and $T_{\min}$ = 1.4°C are the maximal and minimal NH temperature and w is a parameter that sets the maximal extent of the temporal (seasonal) averaging. Thus, during warm interglacial periods ($T \approx T_{\max}$) $\sigma(T)$ is large ($\sigma(T) \approx 2 + w$) and the Gaussian averaging of (3) covers a large part of the annual cycle (no seasonal bias). On the other hand, during cold glacial periods (i.e., T approaching $T_{\min}$) $\sigma(T)$ is small ($\sigma(T) \approx 2$) and the averaging only covers a small part of the annual cycle (stronger seasonal bias).

[21] Figure 3 shows that this formulation still results in an apparent lead of the equatorial SST proxy over the NH temperature. Thus the scenario of a seasonal bias mostly during glacial times also leads to an apparent lead of the equatorial SST even when the equator does not necessarily lead the glacial cycle dynamics. It is difficult to judge from the noisy proxy record whether a lead at all but interglacial times is consistent with the observations.

4. Could Early Sea Level Rise During Glacial Termination Be Masked by Noise?

[22] Consider now an independent argument, related to that made by *Alley et al.* [2002], in which a seeming lead of equatorial SST over sea level does not necessarily indicate that the cause of the terminations lies in the equatorial region. Figure 4a shows time series of observed sea level [*Yokoyama et al.*, 2000] and CO_2 [*Monnin et al.*, 2001] time series for the last glacial termination. Sea level seems to lead initially, its rise starting at 19 kyr while that of CO_2 starts significantly rising only $\approx$2 kyr later. This lag seems significant given the estimated timescale errors in both

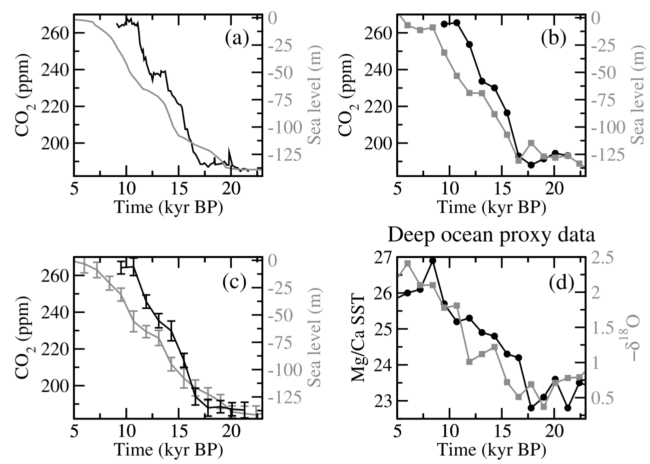

Figure 4. (a) Time series of sea level (shaded line) [*Yokoyama et al.*, 2000] and CO_2 (solid line) from European Programme for Ice Coring in Antarctica dome C [*Monnin et al.*, 2001]. Sea level starts rising at ~19 kyr B.P. leading CO_2 that start rising only at ~17 kyr B.P.; a few kiloyears later, CO_2 rapidly increases and takes the lead over sea level. (b) Same data as Figure 4a plotted at the lower temporal resolution of the *Lea et al.* [2000] data (shown below), with an approximately similar noise level added (see text). The early lead by sea level is masked by the noise preventing its detection. (c) Average ±1 standard deviation of 20 realizations of time series such as shown in Figure 4b. The error bars of the CO_2 the sea level series overlap for the time period between ~16 and ~22 kyr B.P. (d) Equatorial Pacific proxy data of *Lea et al.* [2000] ($\delta^{18}O$, (shaded line) and *SST* (solid line)). High-frequency fluctuations of both $\delta^{18}O$ and SST make it difficult to rule out an early lead of global ice volume.

records. At a later stage CO_2 seems to have risen rapidly and taken the lead at about 16 kyr B.P.

[23] When the time series are plotted at a lower temporal resolution, more characteristic of deep ocean proxies, and when noise is added to these two time series, the initial sea level rise is masked by the noise and CO_2 seems to be leading (Figure 4b). (We use a zero mean Gaussian white noise with a relatively small standard deviation that is 1/20 of the amplitude ranges of the sea level and CO_2 time series; i.e., standard deviation of $(3 - (-145))/20 = 4.4$ m for sea level $(270-182)/20 = 4.4$ ppm for CO_2). Figure 4b shows the result of using one specific noise realization; Figure 4c shows the average ± 1 standard deviation of 20 such realizations. Between the time period of $\sim$22 to $\sim$16 kyr B.P. the error bars of the CO_2 and sea level curves overlap and thus prevent a reliable conclusion regarding the lead or lag of the CO_2.

[24] These observations are relevant to the main point of this paper in two distinct ways. First, if equatorial SST is responding to CO_2 during glacial terminations [*Lea*, 2004], it is possible that sea level rise preceded both the CO_2 and equatorial SST rise initially, but that this initial rise is masked in the proxy records by observational noise (see, e.g., Figure 4d). Such a scenario is consistent with terminations starting because of ice sheet dynamics in the NH, possibly amplified by later feedbacks from the CO_2 and the equatorial ocean and atmosphere [*Gildor and Tziperman*, 2000, 2001]. Second, Figure 4 is relevant here even if the equatorial SST is not strongly coupled to the CO_2. Suppose that sea level rose early during glacial terminations, leading the equatorial SST initially, while the equatorial SST took the lead only at a later stage (as in Figure 4, with equatorial SST replacing the CO_2). In such a case, it is possible that the equatorial SST seems to lead only because proxy noise masks the early sea level rise.

[25] The discussion above regarding the lead and lag of the data presented in Figure 4 is based on visual estimation. It is important to note that in some cases the lead (or lag) may be associated with a specific frequency and that such a lead may not be seen visually; in that case more advanced techniques like the cross-spectral technique [see *Lea et al.*, 2000, supplementary material] may be needed.

5. Conclusions

[26] The admittedly speculative arguments presented here suggest that an observed equatorial SST lead is not necessarily due to the equatorial ocean and atmosphere being indeed the climate system components which started the deglaciations or led the glacial cycles in general. Specifically, we considered the possibilities that an observed equatorial temperature lead may be due to a seasonal proxy bias, or due to proxy noise masking a small early rise and lead of sea level. The main message of this note is that as long as no satisfactory and self-consistent dynamical mechanism in which the equatorial ocean and atmosphere lead global glacial dynamics exists, it is best to note the uncertainties regarding the existence and interpretation of such a lead in proxy observations.

[27] We conclude by noting that even if the equatorial ocean and atmosphere do not lead the glacial cycles or glacial terminations in particular, they may still play an important role in glacial cycle dynamics as an amplifier of a climate signal that was initiated elsewhere. The equatorial and tropical regions affect the global atmosphere and may affect ablation and accumulation of the NH ice sheets via various teleconnections. One must therefore allow for the possibility that the equatorial and tropical dynamics play an important, even if not a leading, role in glacial-interglacial cycles.

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