



Pliocene equatorial temperature: Lessons from atmospheric superrotation

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[1] There is proxy evidence that the pronounced east-west temperature difference observed today across the equatorial Pacific Ocean may not have existed in the early Pliocene (4–5 Ma BP) and that the east Pacific cold tongue developed gradually toward the end of the Pliocene (2 Ma BP). The east Pacific temperature influences weather and climate worldwide, and the Pliocene climate may be an instructive analogue to a future warm climate arising from anthropogenic elevation of CO₂, making understanding the Pliocene equatorial SST gradient especially relevant. A mechanism for maintaining a weaker Pliocene equatorial temperature gradient is proposed that borrows from theories of atmospheric superrotation. The mechanism is based on enhanced or rearranged tropical convective activity during the warmer Pliocene climate exciting atmospheric Rossby waves that propagated poleward from the equator. These waves produced an equatorward flux of westerly momentum that weakened the surface easterlies and therefore the east-west thermocline slope and SST gradient.

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1. Introduction

[2] There is proxy evidence [e.g., *Chaisson and Ravelo*, 2000; *Wara et al.*, 2005] that the presently observed east-west temperature difference across the equatorial Pacific Ocean may not have existed in the early Pliocene (~4–5 Ma BP) but developed gradually toward the end of the Pliocene (~2 Ma BP). This is a dramatic observation given that CO₂ concentration at that time is believed to have been similar to preindustrial values [*Pagani et al.*, 1999] or at most only some 35% higher [*Raymo et al.*, 1996], which would place CO₂ concentration close to present-day values. Globally averaged temperature during the Pliocene is estimated to have been warmer than today's by about 2–3°C.

[3] The present-day equatorial Pacific east-west SST gradient is due to surface easterlies forcing an east-west tilt of the thermocline, bringing cold water close to the surface in the east Pacific. The equatorial easterlies, in turn, are reinforced by the Walker circulation which arises in association with ascent over the west Pacific warm pool and subsidence over the east Pacific cold tongue. In order for this cold tongue to be eliminated, the equatorial surface easterlies and associated Walker circulation would need to diminish, or the thermocline would need to be significantly deeper [*Fedorov et al.*, 2006].

[4] Pliocene climate is often compared to a permanent El Niño state or to the warm phase of the Pacific decadal oscillation [*Fedorov et al.*, 2006; *Molnar and Cane*, 2007]. However, El Niño is quasi-periodic and accounting for a

warmer east Pacific and a permanently reduced east-west temperature gradient state requires, of course, a substantially different physical mechanism. Previous explanations for the vanishing of the equatorial temperature gradient include a (possibly globally) deeper thermocline due to high-latitude fresh water forcing [*Fedorov et al.*, 2004, 2006], opening of the Panamanian seaway [*Haug and Tiedemann*, 1998; *Klocker et al.*, 2005], and a rearrangement of the islands in the maritime continent [*Dayem et al.*, 2007]. The trades may also weaken because of a weakening of the Hadley circulation perhaps in association with a movement of the ITCZ toward the equator. In addition, the Walker circulation in a warming world may also be affected by a dynamical ocean thermostat mechanism leading to a more La Niña-like state [*Clement et al.*, 1996].

[5] We wish to explore an alternative explanation based on the idea that the Pliocene atmosphere was in a dynamical state approaching what is known as “equatorial superrotation,” with surface westerlies, or at least diminished easterlies, in the equatorial Pacific replacing the present-day easterlies. Equatorial superrotation exists on other planets and moons in the solar system including Venus, Titan, Saturn, and Jupiter, and has been explored in the atmospheric literature as a theoretically possible alternate state of the atmospheric general circulation [*Saravanan*, 1993; *Suarez and Duffy*, 1992; *Williams*, 2003, 2006; *Shell and Held*, 2004; *Held*, 1999; *Panetta et al.*, 1987].

[6] The mechanism based on superrotation dynamics is built on the following elements: first that the warmer Pliocene climate resulted in enhanced organized convective activity in the tropical atmosphere including short-term variability similar to Madden-Julian oscillations, westerly wind bursts (WWBs) and convectively coupled waves in the present-day tropical atmosphere. Next, this enhanced organized convective variability acted to stochastically excite tropospheric Rossby waves that radiated away from

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the equator. These waves induced an equatorward flux of westerly momentum that weakened the easterlies or induced westerlies at the equator. The weaker surface Pacific easterlies, in turn, weakened the thermocline slope and therefore also the equatorial SST gradient.

[7] A superrotation state is conventionally characterized by winds that are uniformly westerly at the equator, so that the zonal average winds are westerly as well. While the dynamics of a superrotating atmosphere offers many interesting insights into the pre-ice age climate, we do not advocate that the early Pliocene atmosphere was necessarily superrotating in this strict sense. Rather, we wish to explore the idea that mechanisms leading to superrotation could have participated in substantially weakening the easterlies over the equatorial Pacific.

[8] Before proceeding with the proposed mechanism, it is worthwhile noting that there are many uncertainties regarding the Pliocene observations. First, not all observations agree that there was an east Pacific warming and diminished east-west temperature gradient during the early Pliocene [Rickaby and Halloran, 2005; Groeneveld et al., 2006]. Second, it is very possible that the warming observed in some proxies reflects a changed ENSO frequency [Dowsett and Robinson, 2009], prolonged El Niño events, or other temporal variability that is aliased by the coarse temporal resolution of the deep sea cores into what seems like a permanent warming, a possibility that was carefully explored by some recent modeling studies [e.g., Bonham et al., 2009]. The west Pacific temperature was not necessarily constant during the Pliocene, as seen by Medina-Elizalde et al. [2008] who do observe a reduced east-west temperature gradient during the late Pliocene. It is also important to note that some of the ENSO-like teleconnections observed for the Pliocene can be explained by scenarios other than a warm east Pacific with no ENSO variability [Haywood et al., 2000; Jiang et al., 2005; Sloan et al., 1996]. Keeping in mind these caveats, we proceed to describe a mechanism that may be able to account for a shift in the mean state of the east-west temperature gradient in the equatorial Pacific, should such a shift be the correct interpretation of the proxy observations.

[9] Recognizing that the scenario proposed here is speculative, we present below evidence for each link in the above reasoning chain (section 2). We also discuss the weaknesses of this proposed explanation, contrast it with the available proxy evidence for the Pliocene climate, and explain why current models may be expected to have difficulties testing this mechanism (section 3). We conclude in section 4.

2. Weakening of Pacific Easterlies due to Superrotation Dynamics?

[10] The surface easterlies in the present-day equatorial Pacific result from the influence of two dynamical entities; the first being the east/west Walker circulation. The second is the equatorward airflow associated with the Hadley circulation, which is diverted eastward by the Coriolis force. Although the Walker circulation produces winds in the upper troposphere over the Pacific that are generally westerly, the zonal average upper flow is still easterly [Lee, 1999].

[11] According to Hide's theorem [Hide, 1969] there cannot be zonally averaged westerlies (superrotation) at the equator if angular momentum is conserved following air parcels apart from down-gradient diffusion (that is, diffusion from high values to low values) by turbulent or transient eddy motions. This would preclude superrotation except for the remarkable fact that up-gradient fluxes of momentum and of angular momentum are commonly found in the atmosphere. Denoting deviations from the time mean zonal and meridional velocities by u' and v' , the time mean eddy meridional momentum flux by transient motions such as waves in the atmosphere is $\overline{u'v'}$ where the overbar denotes a time average.

[12] In order to induce westerlies at the equator, we need a momentum flux directed toward the equator, and one way this may occur is via a stochastic excitation of transient motions at the equator. Tropospheric Rossby waves excited at the equator propagate energy away from the equator. Because Rossby wave meridional momentum flux is in the direction opposite to the meridional energy flux of these waves, this induces an up-gradient westerly momentum flux directed toward the equator which acts to weaken the easterlies there.

[13] This raises the issue of possible sources for stochastic forcing of wave motions at the equator, especially in a warm climate such as that of the Pliocene. One obvious candidate is tropical convection. In present-day climate this includes phenomena such as Madden-Julian Oscillations (MJO) [Hendon and Salby, 1994; Madden and Julian, 1971]), the possibly related westerly wind bursts [Weller and Anderson, 1996], and convectively coupled waves [Wheeler and Kiladis, 1999], to name a few examples.

[14] The time mean near-surface zonal momentum equation at the equator balances friction forces, pressure gradient forces, and eddy momentum flux divergence [Holton, 1992, chapter 10],

$$r\bar{u} = -\frac{1}{\rho} \frac{\partial \bar{p}}{\partial x} - \frac{\partial}{\partial y} \overline{u'v'}, \quad (1)$$

where this approximation neglects mean horizontal and vertical advection terms [Shell and Held, 2004], neglects the Coriolis force which vanishes at the equator, and parameterizes friction as linear in the zonal wind. In the above equation r is a friction coefficient, p the pressure, x and y are the east and north coordinates.

[15] In the present Pacific sector climate, the pressure gradient term in (1) results from the east-west SST gradient. Westerlies ($\bar{u} > 0$) would result if this term were weaker while the eddy momentum flux convergence term due to Rossby waves propagating away from the equator was comparatively stronger.

[16] We can now summarize the proposed scenario as follows (Figure 1)

[17] 1. The warmer climate of the Pliocene was characterized by a stronger MJO and WWB-like tropical convection activity that acted as a stochastic excitation at the equator.

[18] 2. Tropospheric Rossby waves radiating energy away from the equator produced an equatorward flux of westerly

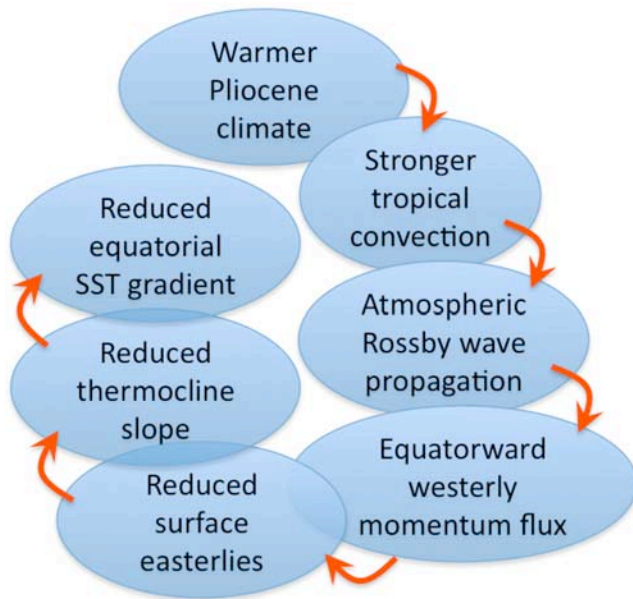


Figure 1. A schematic of the proposed mechanism for the weak Pliocene equatorial Pacific SST gradient.

momentum which tended to weaken or diminish equatorial easterlies.

[19] 3. The weaker easterlies led to a positive feedback: a weaker surface stress decreased the east-west slope of the equatorial Pacific thermocline, deepened the east Pacific thermocline and eliminated the cold tongue in the east Pacific. The diminished east-west SST gradient reduced the atmospheric pressure gradient, further weakened the Walker circulation and perhaps strengthened or rearranged convective activity in the warmer east Pacific leading to more Rossby wave production.

[20] As climate cooled since the early Pliocene (because of reasons we cannot identify here, possibly changes in greenhouse gas concentration), organized tropical convective activity weakened. This led gradually to diminishing of the proposed dynamical regime as the pressure gradient in (1) became dominant over the eddy momentum flux, resulting in gradual establishment of a strong equatorial Pacific SST gradient by 2–3 Ma BP. We now support each step in the above scenario with references to the relevant literature following the same three steps as above.

[21] 1. The atmosphere in a warmer climate contains more moisture and one may therefore expect a stronger or at least reorganized convection-related tropical variability. Indeed, *Slingo et al.* [1999] found an increase in MJO activity since the mid-1970s possibly due to a decadal time scale warming in the tropical SSTs. Similarly, idealized atmospheric general circulation model results support the idea that MJO activity should be stronger in a warmer climate [*Lee, 1999*].

[22] 2. The next stage in the proposed mechanism is divided into several steps. In the first step, stronger or rearranged tropical convective activity results in stronger Rossby wave excitation. While this is a sensible assumption, it cannot

be easily quantified by existing models which have difficulties in producing even the wide range of present-day tropical convective activity. Second, there is a large literature demonstrating that equivalent barotropic atmospheric Rossby waves can be excited at the equator, escape and create remote atmospheric teleconnections [*Hoskins and Karoly, 1981*]. Third and most critical, consider the evidence for stronger wave excitation at the equator leading to weakened surface easterlies. *Lee* [1999] found that a prescribed global SST warming leads both to a stronger MJO and to westerlies at the equator. *Huang et al.* [2001] found a tendency to produce superrotation in a global warming simulation and speculated that this is a result of increased tropical stochastic forcing by atmospheric convection. *Biello et al.* [2007] found tendency to superrotation due to MJO related horizontal momentum flux. *Held and Suarez* [1978] found that minor changes to their convective parameterization could lead to equatorial superrotation. *Held* [1999] later interpreted this result to be the consequence of noise created in this model by the convection scheme (serving the role of the convection-related stochastic excitation proposed here), resulting in Rossby waves propagating off the equator and inducing equatorial superrotation. *Held* also speculated that this scenario may occur under global warming. Finally, B. F. Farrell and P. J. Ioannou (Emergence of jets from turbulence in the shallow water equations on an equatorial beta plane, submitted to *Journal of the Atmospheric Sciences*, 2008) recently explicitly prescribed stochastic forcing representing convective activity in the tropics and found that superrotation resulted in an idealized equivalent barotropic model.

[23] Atmospheric superrotation in models tends to be stronger in the upper troposphere. However, convectively forced Rossby waves propagating away from the equator may lead to weakened easterlies at the surface as well. Equivalent barotropic tropospheric Rossby waves would probably be especially effective for this purpose because they can escape the equatorial waveguide and because they would tend to induce equivalent barotropic momentum forcing at the equator, more likely to lead to a surface signature. The response of surface winds to elevated thermal forcing has been studied, for example, by *Wu et al.* [1999, 2000] and *Chiang et al.* [2001] and turns out to be quite sensitive to model parameters and to the level of the elevated heating. Understanding the surface wind response to possibly elevated eddy momentum fluxes will similarly require a careful further study.

[24] 3. The final step requires no justification, as the relationship between the easterlies, thermocline slope, and east-west temperature gradient is a cornerstone of equatorial dynamics and plays a well known role in the physics of ENSO.

[25] Increase in east Pacific SST may reduce highly reflective marine stratus clouds there, enhancing the warming and leading to yet another positive feedback [*Fedorov et al., 2006; Barreiro et al., 2006*]. The gradual evolution of the SST gradient during the Pliocene indicates that the positive feedbacks do not lead to bifurcations and abrupt transitions. While abrupt transitions are a focus of much of the superrotation literature, bifurcations are not essential for our

mechanism for explaining the vanishing of the Pliocene SST gradient.

3. Successes and Challenges in Explaining Proxy Observations

[26] While offering an explanation for the observed warm SST in the eastern Pacific and diminished east-west temperature gradient [Wara *et al.*, 2005; Ravelo *et al.*, 2004], a successful theory should also be consistent with other Pliocene observations.

[27] The first challenge comes from the observation that midlatitude upwelling zones off Peru, California and southwest Africa were also warmer during the Pliocene. This may be explained either by a global deepening of the thermocline [Fedorov *et al.*, 2004, 2006; Dekens *et al.*, 2007] or by an alternative more consistent with the mechanism suggested here: a shift in the upwelling favorable winds. The water in the Benguela upwelling system off southwest Africa were reconstructed to be 10°C warmer during the Pliocene than today. Increase in the fraction of upwelling diatoms since the Pliocene suggests that this cooling is due to a gradual increase in upwelling, and not necessarily due to a shift in the thermocline depth [Marlow *et al.*, 2000].

[28] Coastal upwelling enhances biological productivity by bringing up nutrient-rich water. If the warming in the upwelling zones is due to a change in the upwelling favorable winds, one may expect a change in productivity. The record on this is mixed, with some evidence that productivity did increase near Peru during the SST cooling, but with no obvious increase off California [Dekens *et al.*, 2007]. These authors suggest that the Peru correlation may be due to tectonic effects, but more direct proxies of upwelling such as used by Marlow *et al.* [2000] may be needed to resolve this issue. High productivity exists today in areas with no coastal upwelling, so that the high productivity off California during the Pliocene does not necessarily reflect upwelling. Especially as there is a shift in the Pliocene plankton species found off California which is not trivially explained by a deepening of the thermocline [Dekens *et al.*, 2007].

[29] Comparison with present-day El Niño events may provide some insights [Molnar and Cane, 2007]. During El Niño the trades weaken and so do the coastal upwelling favorable winds, leading to changes in the wind-driven upwelling off the coast of California [Schwing *et al.*, 2002] and in the surface temperature there, consistent with our mechanism. On the other hand, enhanced coastal warming off California in recent decades may be partially attributed to a depressed thermocline depth there [Mendelsohn and Schwing, 2002].

[30] There is evidence that subtropical winds were different during the Pliocene [Leroy and Dupont, 1997; Molnar and Cane, 2007]. Tropospheric Rossby waves propagating away from the equator and absorbed in the subtropics may lead to the deposition of easterly momentum there. This could change the location or amplitude of the subtropical high-pressure cells which control the location of the upwelling zones. The winds can also change because of the different equator to pole temperature gradient or tropical

atmospheric teleconnections [Dekens *et al.*, 2007]. Careful quantitative model studies together with additional proxies along coastal areas are needed to identify the spatial structure of the Pliocene subtropical atmospheric circulation and upwelling zones and to evaluate the possibility that the cold upwelling zones moved rather than disappeared.

[31] Another indication that changes in thermocline depth may not fully explain changes in equatorial SST gradient is that the equatorial Pacific thermocline depth seems to have shoaled mostly between 5 and 3 Ma, while the east Pacific SST cooled between 2.5 and 1 Ma BP [Wara *et al.*, 2005]. Additionally, the SST started changing at the end of the Pliocene before the start of the Northern Hemisphere glaciation, and as noted by Dekens *et al.* [2007] this means that the shift in upwelling favorable winds could not be due to the glaciation. But this does not rule out other factors that can lead to a change in the winds such as a cooling and a reduction in tropical convective activity and wave momentum flux as suggested here.

[32] The horizontally averaged ocean stratification may be explained either by vertical ocean mixing [Tziperman, 1986], or by cross-isopycnal mixing in the outcrop regions, notably in the Southern Ocean [e.g., Gnanadesikan, 1999]. These processes may have been different during the Pliocene, but the corresponding mechanisms are far from obvious. Overall it seems that the proxy evidence or theoretical considerations cannot rule out either of the two alternative mechanisms for warmth of the coastal zones during the Pliocene, and both a deeper thermocline and changed wind patterns deserve additional examination.

[33] The idea of weaker equatorial easterlies is also challenged by dust records from the east equatorial Pacific [Hovan, 1995] which indicate larger grain sizes during the late Miocene (8–5 Ma BP), possibly due to stronger easterlies then. However, there seems to be no trend in these dust records near the equator itself (sites 848 and 489) for the past 5 Ma when the SST gradient developed. These dust records may also represent the influence of a combination of mean winds and storminess as well as soil moisture, rather than of purely the mean easterlies. The source of dust in these sites is thousands of km away, and pinpointing the dust source and therefore the wind direction is difficult [Molnar and Cane, 2007]. Finally, when easterlies weaken over the central Pacific during El Niño events, they strengthen off central America [Harrison and Larkin, 1998], apparently consistent with both weaker easterlies over the Pacific and with the dust records.

[34] Significantly higher early Pliocene temperature in the high-latitude Ellesmere Island, for example [Tedford and Harington, 2003], may not necessarily be related to the tropics, and may very well be explained by some high-latitude climate feedback such as the convective cloud feedback of Abbot and Tziperman [2008].

4. Conclusions

[35] We propose that wave momentum fluxes forced by enhanced or reorganized tropical convective activity during the warmer Pliocene climate resulted in weakened Pacific easterlies and therefore weakened equatorial SST gradient.

We borrowed from the concepts used to understand atmospheric superrotation, although we do not suggest that the Pliocene atmosphere was necessarily superrotating in the strict sense.

[36] Some current coupled GCMs seem unable to simulate the reduced SST gradient in the Pacific during the Pliocene, although there are also some partial successes in simulating a state consistent with the proxy observations even if it is not necessarily a permanent El Niño state [Haywood and Valdes, 2004; Haywood et al., 2007]. The inability of some GCMs to account for a dramatically reduced temperature gradient may be explained in our proposed scenario by the inability of most of these models to reliably simulate the observed tropical convective activity and the present-day east-west SST gradient without significant biases. These difficulties may have contributed to the inability of most ENSO prediction models to correctly predict the large 1997 El Niño which was accompanied by extreme westerly wind burst activity. Improving these aspects of GCMs is required before the present idea can be tested reliably in model simulations.

[37] An analysis of IPCC model runs under increased greenhouse gas concentration [Vecchi and Soden, 2007] shows a consistent weakening of the Walker circulation.

While this weakening is consistent with thermodynamic moisture budget arguments [Soden and Held, 2006], the mechanism of this weakening from a momentum point of view, and the reason the Hadley circulation does not weaken, are still not clear. Some of the global warming runs showing a weakened Walker circulation also show enhanced extreme precipitation events, and one wonders if these or another enhanced convective activity might act as stochastic forcing which leads to the Walker circulation weakening as discussed here. Finally, the El Niño event of 1997–1998 was judged by Molnar and Cane [2007] to most resemble the early Pliocene climate. This event was also characterized by exceptionally strong westerly wind bursts [McPhaden, 1999], most likely resulting from atmospheric convection processes. Is this a sign of a changing state of the tropics toward one with more convective activity and a weaker mean Walker circulation as also speculated by Held [1999] and Pierrehumbert [2000]?

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