Examining the Tropical Pacific's Response to Global Warming

PAGES 81, 83

The response of the tropical Pacific to increasing greenhouse gases represents an exciting intersection of theory, modeling, and observations. In this article, we contrast competing theories for the response of the tropical Pacific to global warming, illustrate the utility of models for understanding and reconciling these theories, and highlight the need for improved instrumental and paleoclimatic reconstructions to better evaluate the fidelity of current model projections.

There is a long-standing debate in the climate community as to how the tropical Pacific will respond to increased greenhouse gases: Will the structure of changes in the ocean surface temperature more closely resemble an El Niño or a La Niña [e.g., *Knutson and Manabe*, 1995; *Clement et al.*, 1996; *Meehl and Washington*, 1996; *Cane et al.*, 1997; *Cobb et al.*, 2003; *Collins et al.*, 2005; *Vecchi et al.*, 2006; *Zhang and Song*, 2006]? This distinction is of profound significance because conditions in the tropical Pacific affect a range of weather phenomena including tropical cyclone activity, global patterns of drought and flood, agricultural productivity, and oceanic biological activity. The debate extends beyond global warming, with El Niño- and La Niña-like responses being invoked as frameworks for interpreting past climate changes on timescales of centuries to millions of years [e.g., *Koutavas et al.*, 2002; *Stott et al.*, 2002; *Mann et al.*, 2005; *Wara et al.*, 2005].

There is substantial modeling and observational literature advocating the perspective that the response to greenhouse gas forcing will result either in a more El Niño- or more La Niña-like tropical Pacific, and these opposing points of view remain to be reconciled. The mechanisms proposed for both types of response are fundamentally different: Those supporting a more La Niña-like state base their arguments on mechanisms that originate primarily through the ocean, while those that suggest a more El Niño-like state focus on mechanisms rooted in the atmosphere. The terms "El Niño-like" and "La Niña-like" refer to the tendency for the time-mean sea surface temperature (SST) gradient across the equatorial Pacific to either decrease (El Niño-like) or increase (La Niña-like), without implying a change in frequency or intensity of El Niño variability.

Theoretical Basis

The basis for the La Niña-like point of view is the "ocean thermostat" mechanism [*Clement et al.*, 1996; *Cane et al.*, 1997], in which a heating of the tropics leads to an increase in the zonal temperature gradient across the equatorial Pacific. In the eastern equatorial Pacific, where the thermocline is shallow, cooling by upwelling opposes the surface heating to produce a smaller temperature change than in the western Pacific—here the surface temperature response is primarily thermodynamic. The increased zonal SST gradient leads to increased surface easterly winds, driving further cooling by upwelling and further increasing the SST gradient. An El Niño-like response to increased greenhouse gases may be expected since models and theory indicate that the tropical atmospheric circulation should weaken in response to a warming climate [*Betts and Ridgway*, 1989; *Knutson and Manabe*, 1995; *Held and Soden*, 2006]. This weakening is manifested primarily as a reduction in the intensity of the zonal overturning of air across the Pacific (i.e., the Walker circulation) [*Held and Soden*, 2006; *Vecchi and Soden*, 2007] and a decline of the equatorial easterlies that along with other atmospheric feedbacks [*Knutson and Manabe*, 1995; *Meehl and Washington*, 1996], result in a reduction in the equatorial Pacific SST gradient.

Numerical Model Experiments

The mechanisms governing the tropical Pacific's response to global warming emerge from examining various types of climate models, with simplifications made to either the ocean or the atmosphere. For example, in the Cane-Zebiak model used by *Clement et al.* [1996], the representation of atmospheric processes is simplified such that the atmospheric circulation does not weaken in response to a warming. In this configuration, the ocean thermostat mechanism dominates and a La Niña-like state is predicted in response to warming (Figure 1a).

On the other hand, in global climate models (GCMs) that have ocean models with simplified (mixed-layer) representations, the weakened Walker circulation dominates the tropical Pacific response to increased carbon dioxide (CO_2). In this configuration, the effect of ocean dynamics is fixed, eliminating the ocean thermostat but not the weaker Walker mechanism, thus leading to a reduction of the zonal SST gradient, or to an El Niño-like state. This behavior can be seen in the response to CO_2 doubling in 13 models from the Third Coupled Model Intercomparison Project (CMIP3) database (Figure 1b), which archives climate model data used for the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.

But what happens when both mechanisms (the ocean thermostat and the weaker Walker mechanism) are possible? To determine this, we focus on the same set of GCMs as in Figure 1b, but now with a full representation of oceanic and atmospheric processes. These GCMs still show relatively zonally uniform warming, with a slightly larger warming in the central Pacific than in the western Pacific (Figure 1c). Clearly, the "El Niño-ness" of the signal is diminished relative to the same set of GCMs without ocean dynamics (Figure 1b). We suggest that the reduced El Niño-ness of the response in models with active ocean dynamics, relative to that from mixed-layer models, results from a superposition of both the ocean thermostat and the weaker Walker mechanisms. Further analysis is necessary to quantify the relative influence of these, and possibly other, mechanisms.

Current model projections do not show a systematic response of their El Niño variability to global warming [e.g., *Merryfield*, 2006]. Though changes in the mean state of the Pacific provide a foundation to understand the response of El Niño variability to global warming, the intensity, frequency, and character of El Niño involve a variety of physical processes whose responses to increased greenhouse gases are not well constrained by current models.

Instrumental Measurements

A resolution of the mechanisms active within GCMs is not sufficient to settle the dispute over the response of the tropical Pacific to greenhouse forcing. For this, we must turn to observations. We compare centennial trends in SST from two different reconstructions of SST in Figures 1d and 1e. One reconstruction—HadISST [*Rayner et al.*, 2003]—shows a La Niña-like pattern, with an increase in the zonal SST gradient, through robust warming in the west and weak changes (including modest cooling) in the east, in qualitative agreement with *Cane et al.* [1997]. However, the U.S. National Oceanic and Atmospheric Administration's (NOAA) extended reconstruction of SST (ERSST) [*Smith and Reynolds*, 2004], shown in Figure 1e, exhibits an El Niño-like pattern, with more warming in the east than in the west. The structure of the ERSST trends is consistent with recent analyses of sea level pressure data indicating a weakening of the Walker circulation [*Vecchi et al.*, 2006; *Zhang and Song*, 2006]. This discrepancy leaves scientists unable to confirm the fidelity of the models' partitioning of the different processes that would lead to El Niño- and La Niña-like responses.

The time series of the west-east difference of SST across the Pacific (δ_xSST) provides hints as to the source of the discrepancies (see Figure 2, in the electronic supplement to this *Eos* issue; http://www.agu.org/eos_elec). Over most of the period of 1880 to the present, the evolution of the two reconstructions of δ_xSST is quite similar, with the timing and amplitude of local maxima and minima corresponding across

By G. A. Vecchi, A. Clement, and B. J. Soden

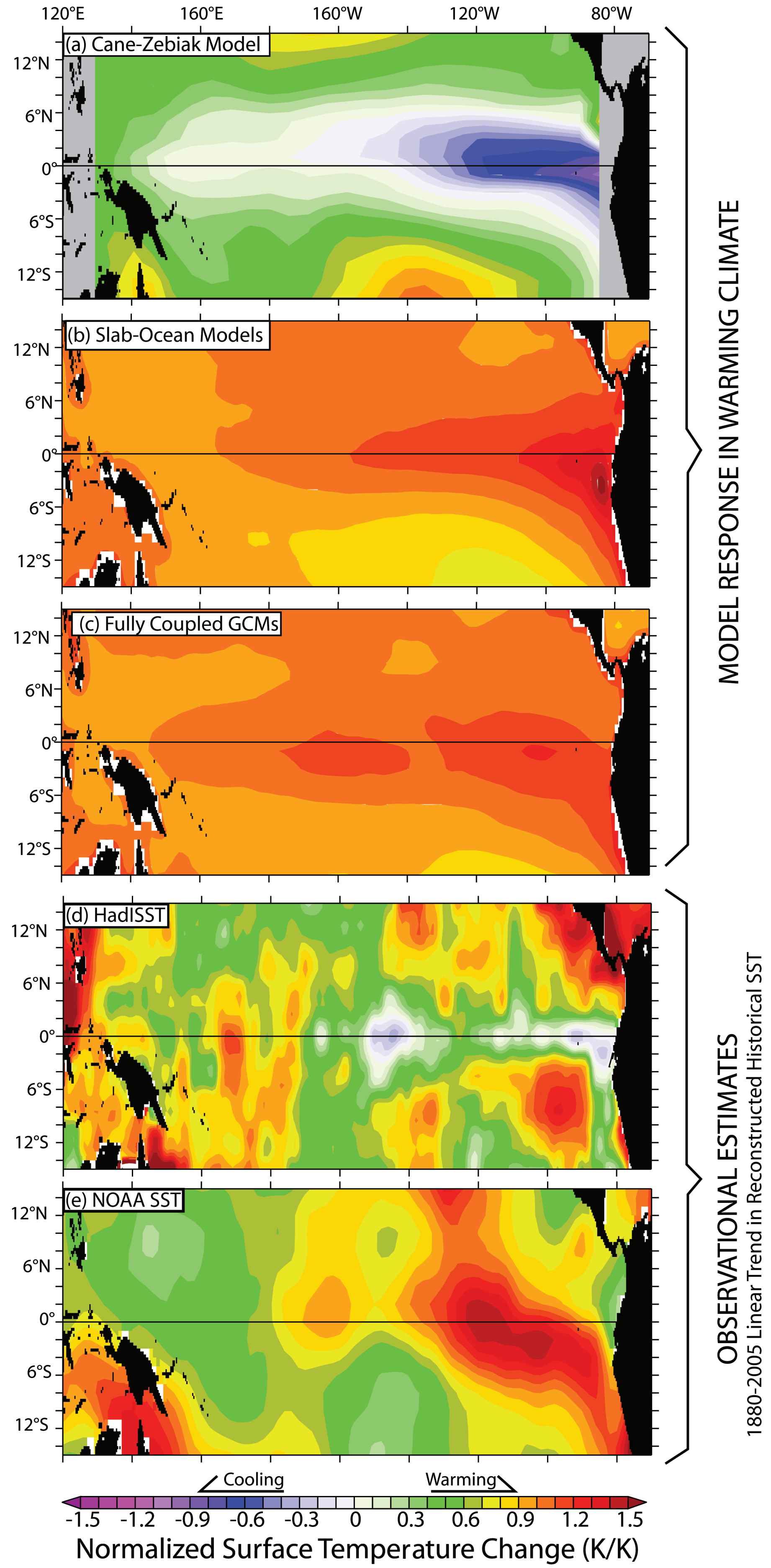


Fig. 1. Response of coupled models of varying complexity to a warming climate and observational estimates of the long-term trend in Pacific sea surface temperature (SST), normalized by tropical-mean SST change: (a) response of the Cane-Zebiak model to an imposed surface warming of 2 K, normalized by 2 K (adapted from Clement et al. *[1996]); ensemble-average response of SST to CO_2 doubling from 13 global climate models (GCMs) from the CMIP3 model database in (b) a mixed-layer ocean GCM and (c) fully coupled GCM configurations; 1880–2005 trends from the reconstructions of observed SST are from (d) HadISST and (e) ERSST.*

the different SST products. However, the long-term behavior of the two reconstructions is different between the products over two periods of time, around the 1930s and 1980s. These periods are roughly coincident with the period of greatest change in "bucket-to-intake" correction of SST measurements (a correction that differs between the products, which is applied to account for changes in measurement techniques at sea, from using buckets lowered into the water to using ship engine room water intake) and the beginning of satellite infrared SST retrievals (satellite data are used in HadISST but not in ERSST), respectively. Effort should be concentrated toward identifying the specific sources of this discrepancy and the appropriate corrections.

Proxy Data

Another way forward to assess whether century-scale changes in Pacific conditions have been El Niño- or La Niña-like may be through reconstructions of local temperature and salinity using coral skeletons from the tropical Pacific over the historical record. Currently, there are only a handful of published data sets that can address this issue. Some coral records suggest a trend toward warmer and wetter conditions in the central Pacific at the end of the twentieth century [e.g., *Cobb et al.*, 2003; *Urban et al.*, 2000]. Taken at face value, these records would suggest an eastward shift of warm pool convection and more El Niño-like conditions. However, coral records from the region of the South Pacific convergence zone suggest that since the mid-1880s there has been an eastward expansion of rainfall, as occurs during La Niña events [*Linsley et al.*, 2006].

A more complete picture of the evolution of tropical Pacific climate in the twentieth century will emerge from additional records from various locations incorporated into a multiproxy, synthesized approach. For example, *Evans et al.* [2002] have constructed a framework for analyzing numerous coral records to extract spatially and temporally coherent signals. Because the discrepancies in the reconstructions of δ_xSST arise primarily in two discrete periods (see supplementary Figure 2), proxy observations spanning these periods could prove particularly useful.

Theory, models, and observations present diverging views of the Pacific response to global warming. It may be possible to reconcile the different theoretical frameworks for understanding the Pacific response to increased CO_2 within state-of-the-art coupled GCMs. However, the test of whether the tropical Pacific has become more El Niño- or more La Niña-like is in the hands of the observationalists, and the consequences for our understanding of the climate in the tropical Pacific and in all the regions affected by El Niño/La Niña are great.

Acknowledgments

We are grateful for comments and suggestions from T. Delworth, T. Knutson, A. Wittenberg, and B. Linsley. This work has been funded in part by the NOAA Office of Global Programs and the U.S. National Science Foundation's Paleoclimate program. The CMIP3 model data were made available by the Program for Climate Model Diagnosis and Intercomparison at the U.S. Department of Energy's Lawrence Livermore National Laboratory, Calif.

References

Betts, A. K., and W. Ridgway (1989), Climatic equilibrium of the atmospheric convective boundary layer over a tropical ocean, *J. Atmos. Sci.*, *46*(7), 2621–2641.
Cane, M. A., et al. (1997), Twentieth-century sea surface temperature trends, *Science*, *275*(5302), 957–960, doi:10.1126/science.275.5302.957.
Clement, A. C., R. Seager, M. A. Cane, and S. E. Zebiak (1996), An ocean dynamical thermostat, *J. Clim.*, *9*, 2190–2196.
Cobb, K. M., C. D. Charles, H. Cheng, and R. L. Edwards (2003), El Niño/Southern Oscillation and tropical Pacific climate during the last millennium, *Nature*, *424*, 271–276.
Collins, M., et al. (2005), El Niño- or La Niña-like climate change?, *Clim. Dyn.*, *24*(1), 89–104.
Evans, M. N., A. Kaplan, and M. A. Cane (2002), Pacific sea surface temperature field reconstruction from coral δ^{18}O data using reduced space objective analysis, *Paleoceanography*, *17*(1), 1006, doi:10.1029/2000PA000590.
Held, I. M., and B. J. Soden (2006), Robust responses of the hydrological cycle to global warming, *J. Clim.*, *19*, 5686–5699.
Knutson, T. R., and S. Manabe (1995), Time-mean response over the tropical Pacific to increased CO_2 in a coupled ocean-atmosphere model, *J. Clim.*, *8*, 2181–2199.
Koutavas, A., J. Lynch-Stieglitz, T. M. Marchitto Jr., and J. P. Sachs (2002), El Niño-like pattern in ice age tropical Pacific sea surface temperature, *Science*, *297*(5579), 226–230, doi:10.1126/science.1072376.
Linsley, B. K., A. Kaplan, Y. Gouriou, J. Salinger, P. B. deMenocal, G. M. Wellington, and S. S. Howe (2006), Tracking the extent of the South Pacific Convergence Zone since the early 1600s, *Geochem. Geophys. Geosyst.*, *7*, Q05003, doi:10.1029/2005GC001115.
Mann, M. E., M. A. Cane, S. E. Zebiak, and A. Clement (2005), Volcanic and solar forcing of the tropical Pacific over the past 1000 years, *J. Clim.*, *18*(3), 447–456.
Meehl, G. A., and W. M. Washington (1996), El Niño-like climate change in a model with increased atmospheric CO_2 concentration, *Nature*, *382*, 56–60.
Merryfield, W. J. (2006), Changes to ENSO under CO_2 doubling in a multimodel ensemble, *J. Clim.*, *19*(16), 4009–4027.
Rayner, N. A., D. E. Parker, E. B. Horton, C. K. Folland, L. V. Alexander, D. P. Rowell, E. C. Kent, and A. Kaplan (2003), Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century, *J. Geophys. Res.*, *108*(D14), 4407, doi:10.1029/2002JD002670.
Smith, T. M., and R. W. Reynolds (2004), Improved extended reconstruction of SST (1854–1997), *J. Clim.*, *17*, 2466–2477.
Stott, L., C. Poulsen, S. Lund, and R. Thunell (2002), Super ENSO and global climate oscillations at millennial time scales, *Science*, *297*(5579), 222–226, doi:10.1126/science.1071627.
Urban, F. E., J. E. Cole, and J. T. Overpeck (2000), Influence of mean climate change on climate variability from a 155-year tropical Pacific coral record, *Nature*, *407*, 989–993.
Vecchi, G. A., and B. J. Soden (2007), Global warming and the weakening of the tropical circulation, *J. Clim.*, *20*(17), 4316–4340.
Vecchi, G. A., et al. (2006), Weakening of tropical Pacific atmospheric circulation due to anthropogenic forcing, *Nature*, *441*(7089), 73–76, doi:10.1038/nature04744.
Wara, M. W., A. C. Ravelo, and M. L. Delaney (2005), *Science*, *309*(5735), 758–761, doi:10.1126/science.1112596.
Zhang, M., and H. Song (2006), Evidence of deceleration of atmospheric vertical overturning circulation over the tropical Pacific, *Geophys. Res. Lett.*, *33*, L12701, doi:10.1029/2006GL025942.

Author Information

Gabriel A. Vecchi, NOAA Geophysical Fluid Dynamics Laboratory, Princeton, N. J.; E-mail: gabriel.a.vecchi@noaa.gov; and Amy Clement and Brian J. Soden, Rosenstiel School for Marine and Atmospheric Science, University of Miami, Florida.

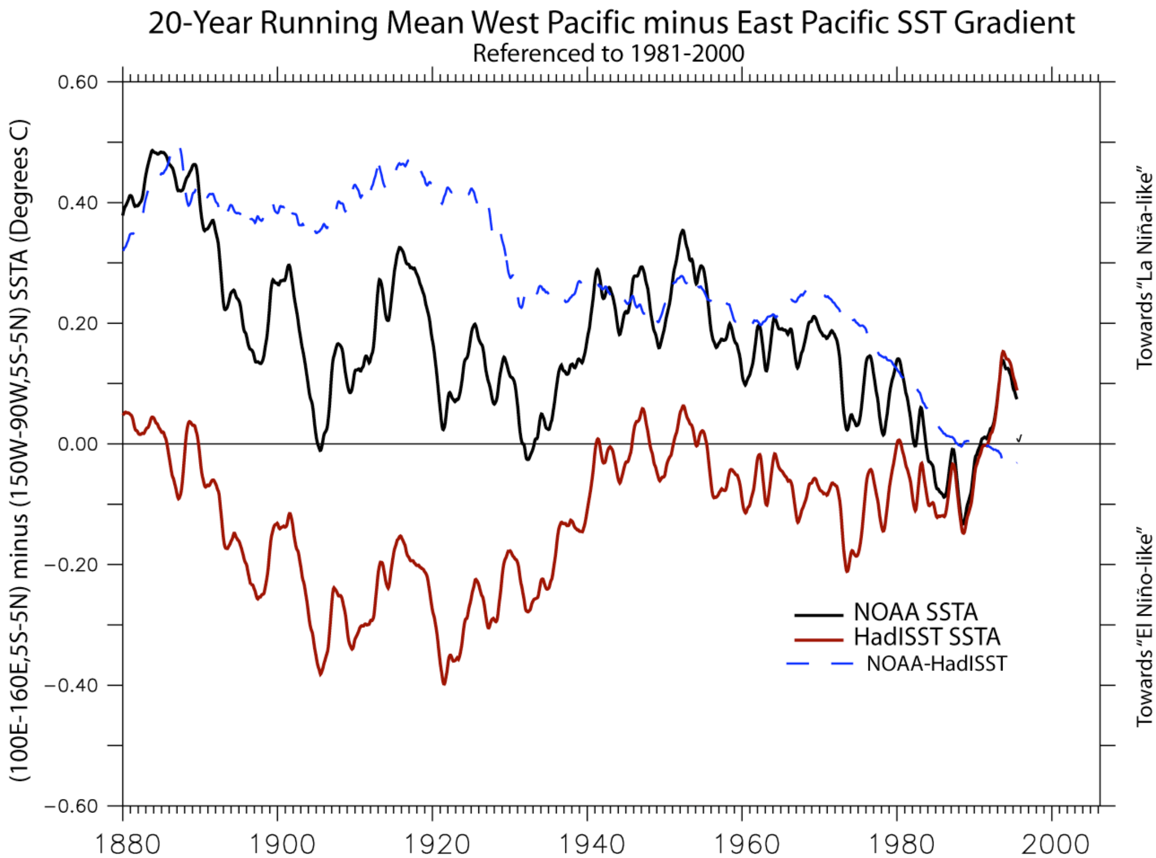
Climate Warming and 21st-Century Drought in Southwestern North America

PAGE 82

Since 2000, southwestern North America has experienced widespread drought. Lakes Powell and Mead are now at less than 50% of their reservoir capacity, and drought or fire-related states of emergency were declared this past summer by governors in six western states. As with other prolonged droughts, such as the Dust Bowl during the 1930s, aridity has at times extended from northern Mexico to the southern Canadian prairies. A synthesis of climatological and paleoclimatological studies suggests that a transition to a more arid climate may be occurring due to global warming, with the prospect of sustained droughts being exacerbated by the potential reaction of the Pacific Ocean to warming.

An analysis of 19 climate models by *Seager et al.* [2007] concluded that the transition to a more arid climate in southwestern North America is imminent due to increased air subsidence in the subtropics as the tropics warm and as equatorial convection increases. The Pacific Ocean may play an important role in generating prolonged droughts as warming continues.

Paleoclimatic studies provide insights into how the Pacific Ocean and North American hydrometeorology have responded to past climate warming. A pertinent lesson comes from the Medieval Climate Anomaly (MCA; 800–1300 A.D.). During the MCA, increased irradiance coupled with a lull in volcanic activity produced increased radiative forcing (Figure 1a) and climate warming. The MCA is associated with widespread aridity and increased fires in western North America [*Cook et al.,* 2004]. A pronounced confluence of increased solar forcing and



Supplementary Figure: Time-series of 20-year mean west minus east Pacific SST for three reconstructions of observed SST (solid lines) and for the difference of the ERSST reconstruction to the other two reconstructions (dashed lines). Units are Kelvin, and positive values indicate a more "La Niña-like" state. Data have been referenced to 1981-2000.