Perspective

Climate change and the tropical Pacific: The sleeping dragon wakes

R. T. Pierrehumbert*

Department of Geophysical Sciences, University of Chicago, Chicago, IL 60637

The global impact of the tropical Pacific atmosphere–ocean system has been extensively studied in connection with the El Niño cycle. There is reason to believe that the system may also hold the key to rapid reorganizations of climate leading to changes that persist from centuries to millennia.

The unusually steady climate of the past 10,000 years, after the ultimate recovery from the Younger Dryas cold reversion, has provided a congenial home for the rise of civilization. This era contrasts with the Last Glacial Maximum and other cold periods of the Pleistocene, which were beset by erratic, rapid, and large-amplitude climate reorganizations with no obvious astronomical pacemaker. The mechanism of these millennial scale climate changes is not known (see ref. 1 for some current thinking on the matter); given that we don't know what accounts for the unusual stability of the recent climate, we don't know what it would take to break it. This thought is unsettling in a world seemingly committed to substantial warming from anthropogenic CO_2 increases in the next 2 centuries.

Attention has focused on the Atlantic thermohaline circulation (THC) as the "Achilles heel" of climate, primarily because many of the abrupt climate change events of the past 100,000 years are known to have been accompanied by abrupt transitions in the THC (2). There is a need to consider other possibilities, not least because atmospheric general circulation models fail to respond to a THC shutdown with a global signal of the character and magnitude that seems to be called for by the data. Is the failure of atmospheric models to yield the required response symptomatic of some fundamental flaw in the current models, or is the resolution of the puzzle to be found in some trigger other than THC shutdown? The answer to this question would tell us much about the confidence one can put in climate model predictions.

Several energy flows that powerfully affect our climate come to a confluence in the tropical Pacific. The stirrings of this region are currently thought of mainly in connection with the coming and going of El Niño, which has a global impact but only on the 3- to 5-year time scale. There is a growing awareness that related processes have the potential to participate in more ponderous climate variations.

Ocean Heat Transports: Pacific vs. Atlantic. Oceans influence the Earth's climate by transporting heat. This transport is accomplished by moving warm near-surface waters poleward, where they cool by releasing their heat to the atmosphere. To sustain the cycle, the newly cooled waters must somehow return to the tropical or subtropical surface, where they can be heated anew. Although water must be brought to the surface to warm or cool, the return path for cold water can take on a number of different configurations. On one extreme, it can sink to the deep ocean and later upwell to the surface. On the other, it can move equatorward as part of a wind-driven recirculating gyre near the surface. Either way, the heat transport rate is $\rho c_p F \Delta T$, where ρ is the mean density of the sea water involved, c_p is its specific heat, F is the volume rate of water exchanged, and ΔT is the temperature difference over which the cycle works.

In thinking about oceanic heat transports, 1 PW (10^{15} W) is a convenient number to keep in mind. The Atlantic THC accounts for roughly 1 PW of transport into the North Atlantic and dominates the Atlantic oceanic transport. This transport is accomplished by a volume exchange of about 15 Sverdrup (10^6 m^3/s) operating on a temperature difference of about 17°C, which is half the maximum ΔT available in the present ocean. Pacific heat transport estimates range from 0 to 1 PW northward across 2°N and 2–3 PW southward across 20°S (3–5). [Typo: 20N, not 2N]

The overturning THC that dominates Atlantic transport is very "tippy," in the sense that the intensity and vertical structure of the circulation are sensitive to the parameters of the problem. Specifically, the North Atlantic waters are salty enough that small changes in temperature or freshwater input can tip the balance from conditions in which North Atlantic deep water forms to conditions in which it does not. Deep water does not presently form in the North Pacific, though the episodic appearance of oxygen-rich waters in the normally anoxic Santa Barbara Basin at 500-m depth indicates that during extremely cold periods in the past there may have been some limited local ventilation of the Pacific thermocline (6). The heat transport from the tropics to the North Pacific is accomplished almost exclusively by a shallow recirculating near-surface flow, in which the Kuroshio current is a major participant. Transport from the tropical Pacific southward involves a set of vertical overturning cells of relatively small vertical scale compared with the Atlantic THC (5).

Deep and intermediate waters form on the margin of Antarctica. The water mass of most interest to us is the Antarctic intermediate water (AAIW), which forms through the agency of mixing in the Antarctic circumpolar current and wind-driven upwelling and travels equatorward at a depth of 500–1,500 m with a mean temperature of 5°C. This water blends with subducted subtropical waters to form the subthermocline waters that are tapped by a combination of upwelling and vertical mixing in the tropical Pacific. There is thus an intimate link between events on the margin of Antarctica, and the tropical Pacific processes that govern both El Niño and Pacific oceanic heat transport. The Atlantic tropics are evidently more decoupled from the AAIW, because this water mass crosses the equator relatively unimpeded in the Atlantic.

Another important difference between the Atlantic and Pacific is that the heat transport is northward throughout the entire Atlantic, including the Southern Hemisphere. About half of the heat delivered to the North Atlantic passes through and under the tropical Atlantic, rather than originating there. In contrast, the Pacific has a more intuitive diffusive heat transport, with tropical Pacific heat being exported to both hemispheres. The bias of Pacific heat transport to the south reflects the need to supply the South

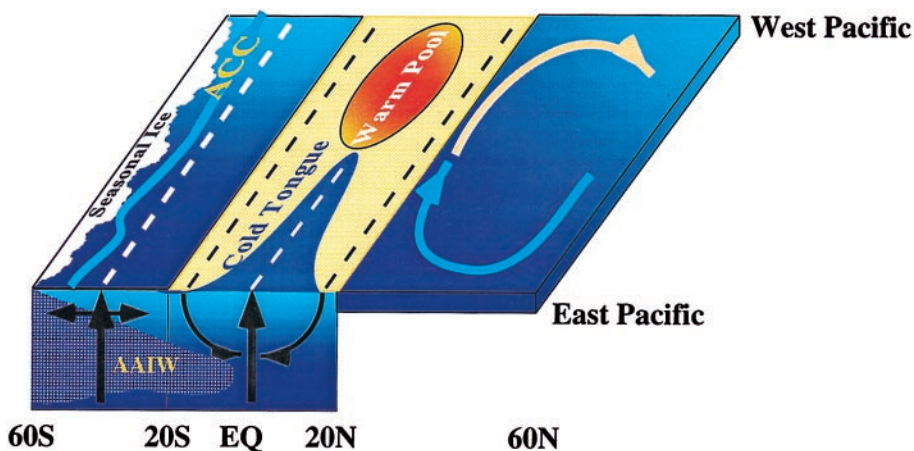*To whom reprint requests should be addressed. E-mail: rtp1@geosci.uchicago.edu.

PERSPECTIVE

SPECIAL FEATURE

Fig. 1. Schematic of heat-transporting circulations in the upper 1.5 km of the Pacific Ocean. ACC, Antarctic circumpolar current. White dashed lines indicate regions of upwelling, and black dashed lines indicate regions of downwelling. The cold-tongue upwelling in the tropics is sensitive to the tropical Easterly winds. AAIW formation is affected by the wind-driven upwelling associated with Antarctic westerlies, by the creation of dense water caused by brine being rejected from freezing sea water, and by lateral mixing within the ACC.

Atlantic (through the Antarctic circumpolar current) with the heat it is moving northward.

As an idealization, suppose that the tropical latitudes encompass half the area of the globe and that each of the Northern and Southern extratropics make up a quarter. Then, a transport of 1 PW from each edge of the tropics averages out to a cooling influence of 8 W/m^2 in the tropics and a compensating heating of 8 W/m^2 in the extratropics. A heat flux of this magnitude has to be reckoned as a rather big deal, being comparable, locally, to the direct radiative forcing caused by changing atmospheric CO_2 by a factor of four in either direction. However, as with CO_2, the effect is not so big a deal that it can lead to substantial climate changes without the help of amplifying feedbacks caused by water vapor and sea-ice–albedo feedbacks.

Fig. 1 summarizes the configuration of Pacific heat transports today, insofar as our still inadequate ocean data permit. Is the system tippy enough to undergo abrupt transitions? What are the points of vulnerability of the system that could trigger a transition? How would the atmosphere respond to such transitions?

Atmospheric Transitions. The tropical atmosphere itself has scope for reorganizations that could lead to rapid climate transitions.

The large-scale tropical atmospheric circulation consists of a deep overturning meridional (Hadley) and zonal (Walker) cell. The two circulations interact and cannot always be disentangled into distinct components. These cells organize convection, with the subsiding branches leading to continent-sized regions of dry,

clear air subject to little or no deep convection. Deep convection over the Pacific occurs in the extensive ascending region associated with the Western Pacific warm pool and in the narrow and intense line-like feature known as the intertropical convergence zone (ITCZ). The regions of ascent are connected to, but not precisely identical with, the regions of warmest ocean waters. The warm pool has no intrinsic cloud, evaporative, or thermodynamically based "thermostat," and in the absence of heat exports to the extratropics would escalate from its present temperature of 29°C to temperatures of 47°C or even more (7, 8).

The formation of convecting air is tippy in precisely the same sense and for precisely the same reason that formation of North Atlantic deep water is tippy. The tropical atmosphere is very nearly neutrally buoyant with regard to moisture-laden air parcels that release the latent heat of their moisture as they ascend. Hence, a small change in the moisture and temperature of the tropical boundary layer (relative to the overlying air) suffices to determine whether a region produces sufficient buoyancy to convect. Tropical convection creates "top air" in much the same way oceanic convection creates "bottom water."

The Hadley and Walker cells also determine the surface winds that govern upwelling and the upward tilt of the thermocline as one proceeds eastward. Both processes bring cold waters to the surface in the Eastern Pacific, creating the cold tongue that allows these waters to gain heat from the atmosphere and sustain the cycle of Pacific oceanic heat transport.

The water vapor feedback is the premier atmospheric feedback amplifying the

response to what would otherwise be minor climate forcings. Reorganizations of tropical convection have a profound effect on the water vapor pattern of the tropical Pacific, both through changes in the location and area of the convective moisture-source region and through changes in the intensity of subsidence of the air, which alters the dryness of the nonconvective regions. An example of the reorganization of water vapor can be seen in Fig. 2, where we compare the water vapor pattern in the middle troposphere between Jan. 1, 1983 (an El Niño year) and Jan. 1, 1985 (a La Niña year). Recent satellite analyses confirm that in the Southern summer, the Northern subtropics become drier during the strong El Niños of 1985 and 1997 (J. Bates, personal communication). The mechanism determining subtropical humidity offers possibilities for rapid climate reorganization. It has been shown that subtropical moisture content drops dramatically if lateral mixing by tropical transient eddies is inhibited and that the resulting reduction powerfully affects the Earth's radiation budget (8–10). Moist air plumes invading the otherwise dry Northern subtropics can be seen in Fig. 2, and they seem to be more sparse during the El Niño year.

The theoretical idealization of a longitude-independent Hadley circulation applies most accurately to the Pacific, because the wide ocean basin permits an atmospheric circulation that varies little with longitude, particularly during El Niño years. In simplified models, the mass and energy transport carried by the Hadley cell intensifies as the ITCZ is moved further from the equator (11). This mechanism of intensification provides interesting possibilities for climate shifts, because convection could reorganize in such a way as to shift the ITCZ, either through autonomous variability of the coupled atmosphere–ocean system or in response to orbital changes in the insolation pattern. Andes ice core data indicating that Sajama at 18°S was cold and wet at times when Huascaran (9°S) was cold and dry are suggestive of some kind of shift in the ITCZ in concert with millennial variations (12).

All of the above circulations can affect the formation of boundary layer clouds. Such clouds can have an albedo approaching that of ice and exert a potent cooling effect when they form. Subtle changes in the boundary layer can lead to the formation or dissipation of such clouds and can lead to highly significant climate feedbacks (13).

As a nexus for climate change, the tropical Pacific also has a clear advantage over the North Atlantic, in that the global atmosphere is exquisitely sensitive to tropical Pacific sea surface temperature anom-
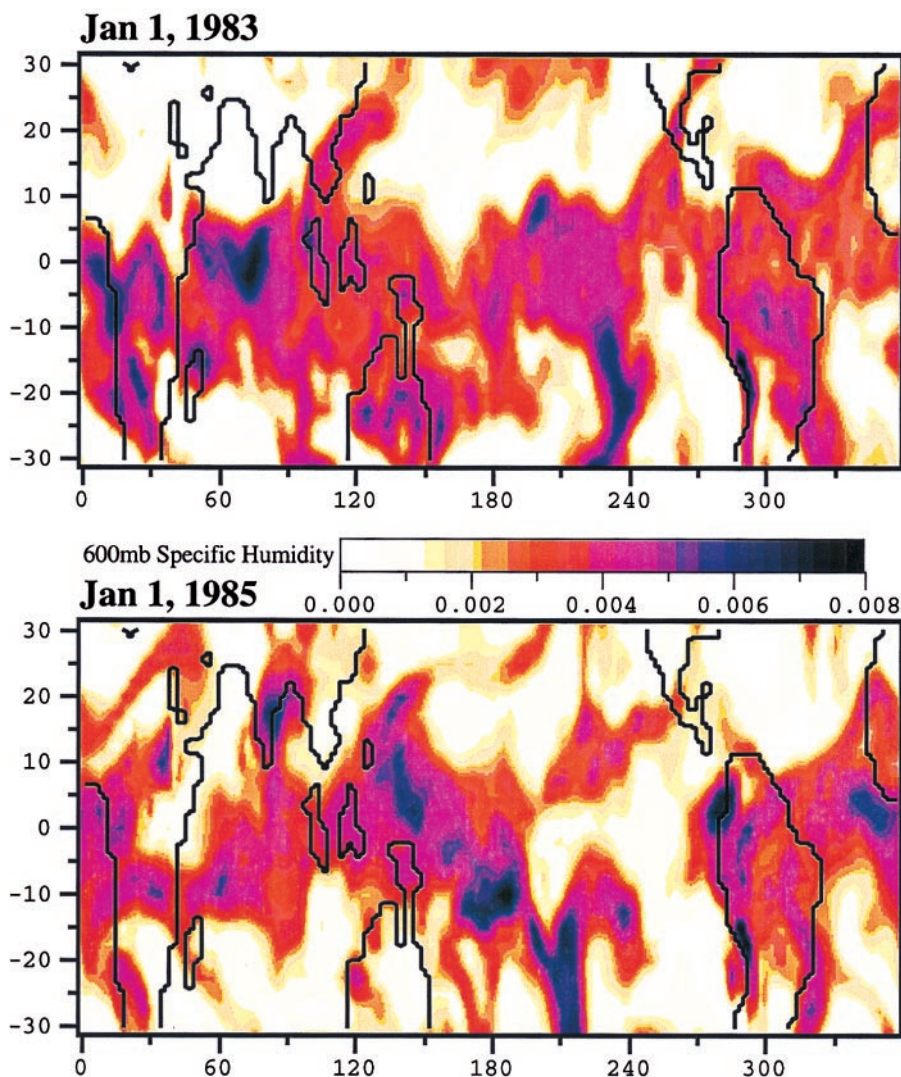
Jan 1, 1983

Jan 1, 1985

Fig. 2. Water vapor concentration (as mass-mixing ratio) in the mid troposphere on January 1, 1983 and January 1, 1985. The former is an El Niño year, whereas the latter is a La Niña year. Data are taken from the National Center for Environmental Prediction analysis. In the El Niño year, the Pacific moist air undergoes a reorganization and makes up an uninterrupted band south of 10°N, whereas the Northern Pacific subtropics consists of an unbroken dry-air pool. In the La Niña year, moist air is found predominantly in the Western Pacific, and an equator-straddling dry pool is found near 240°E.

alies. It has been said that "the temperature in Spitzbergen is more sensitive to the tropical Pacific than it is to the North Atlantic" (T. Palmer, personal communication). This sensitivity is captured in atmospheric models and is mediated by well established physical mechanisms such as modulation of deep convection and changes in the strength of the subtropical atmospheric jet. The connection is long familiar from discussions of El Niño; Cane (14) has recently discussed a particularly clear-cut example and suggested that such teleconnections could also play a role in initiation of major glaciation and deglaciation.

Is El Niño Changing? The West Pacific warm pool, the East Pacific cold tongue, and the atmospheric Hadley and Walker circulations form a tightly coupled system. To some extent, it can be modeled by coupling the upper tropical Pacific Ocean to the atmosphere, without needing to solve the whole world ocean circulation problem. El Niño is a self-excited oscillation of this delicately balanced system. With the recent warming of climate, its character seems to be changing to favor more frequent and higher amplitude events (15). Further, the El Niño revealed in the pre-1976 instrumental record has a frequency spectrum almost identical to that of paleo-El Niños recorded in coral sequences from the previous major interglacial period (123,000 years ago), whereas the post-1976 spectrum is distinctly different (16). Thus, the recent behavior of El Niño

seems to represent something outside the ordinary range of behavior in a pristine interglacial period, though of course the case would be made stronger by the recovery of more El Niño data from other times in the previous interglacial period and from other sites.

On sufficiently long time scales, the tropical Pacific system couples to the world ocean, because the equatorial thermocline structure determines the environment for upwelling and therefore the connection between surface wind and sea surface temperature, which is the key to the behavior of the coupled system. Our concern here is not so much with the impact of a more vigorous El Niño—indeed a big enough concern—but rather with whether the apparent changes in El Niño are a warning sign for larger changes brewing in the Pacific circulation. A recently obtained record of bomb-produced ^{14}C in coral suggests that such changes may be underway (17). Deep water is deficient in ^{14}C compared with surface waters, because there hasn't been enough time since the era of atmospheric nuclear testing for the ^{14}C to penetrate. Thus, low ^{14}C at the surface indicates that upwelling is able to tap into deep waters that have not been recently ventilated. Normally, the tropical Pacific has rather low ^{14}C concentrations during the upwelling season. The new coral data show an abrupt increase in ^{14}C in the upwelling season starting in 1976, precisely the year when the instrumental record begins to show a change in the character of El Niño. This increase has been interpreted as indicative of a shift in the equatorial thermocline structure, associated with a change in the source waters for the thermocline in favor of recently subducted subtropical surface waters (17). It would also be consistent with a reduction of the admixture of AAIW into the tropical upwelling.

The Antarctic connection offers a rich variety of interesting possibilities. The wind-driven upwelling in the Southern Ocean girdling Antarctica affects both the volume flow of the AAIW and the tropical thermocline depth (18). Hence, a small shift in the wind stress pattern around Antarctica could change the environment, modulating the behavior of the tropical Pacific. Further, because rejection of brine from ice formed at the Antarctic margin plays a role in formation of dense waters there, changes in the Antarctic ice margin could have repercussions in the tropical Pacific and from there to the rest of the globe. Modelers should note that the AAIW flow is also sensitive to the representation of lateral mixing in the Antarctic circumpolar current and to vertical diffusion in the tropics (18).

An involvement of the Antarctic margin is also suggested by ice-core data showing

that the whole Antarctic continent responds to millennial scale variability but not as a unit; some sites show cold events in phase with Greenland ice cores, whereas others give an out of phase behavior (19). At present, there are too few Antarctic cores to allow the mapping of the spatial pattern of the response. Much could be learned from a well chosen series of new cores near the Antarctic coast.

The nonlinear response of the coupled Hadley–Walker and cold tongue systems to orbital insolation fluctuations on the precessional time scale (22,000 years) may be sufficient to yield substantial millennial scale variability, even without involving changes in AAIW (20, 21). This intriguing possibility has been explored only in highly simplified models that do not adequately resolve the full range of vertical transport processes in the ocean or the dynamics of the atmospheric Hadley cell and its influence on water vapor feedback. Pressing forward in the direction of more realism would be a fruitful target for the application of terascale computing in the coming years.

Surprises from the Pacific? If surprises could be fully anticipated, they wouldn't be surprises. Nonetheless, the above considerations suggest a few places that bear watching. Chief among these is the nexus of processes around the Antarctic margin, especially given that in recent years we have seen a significant retreat of sea ice and shelf ice around the Antarctic, and more is expected as the world warms. It is harder to think of ways in which the North Pacific heat flux could suddenly switch, because it is harder to tip the wind-driven gyre with small changes in boundary conditions. However, the Kuroshio current does show some signs of bimodality, which could participate in mode switches.

Whatever the world ocean does, the tropics may respond with some surprising reorganizations of convection. There is nothing inevitable about the present configuration of warm pool, cold tongue, and ITCZ. The delicacy is revealed both in the fact that atmosphere–ocean general circulation models have difficulty getting the basic climatology right and in analyses of simplified coupled models (22, 23). Atmospheric models that do not impose an east–west sea surface temperature gradient in the Pacific tend to collapse convection into a thin ITCZ near the Equator, leading to vastly greater dominance of the subsiding regions.

One of the more exotic possibilities is that a strengthening of the temperature contrast between the warm pool and the cold tongue could lead to a complete breakdown of the system of tropical easterly trade winds known since time immemorial. This breakdown could happen, if a tropical sea surface temperature anomaly forces a Rossby wave that carries easterly pseudomomentum away from the tropics, leading to a local westerly acceleration. If the forcing were strong enough, the westerly acceleration could overwhelm the easterly Coriolis acceleration caused by equatorward drift in the Hadley cell, whereupon the normal tropical winds would be replaced by a westerly superrotation. If the westerlies were to penetrate to the surface, the normal equatorial upwelling in the ocean would be replaced by downwelling, and other far-reaching climate changes would ensue. The superrotating state is well documented in idealized two-layer models (24) and has been found by several investigators employing realistic multilevel general circulation models (I. Held and D. Hartmann, personal communications; see also ref. 25). There is no evidence that a westerly superrotating state has ever occurred in any climate of the Earth's past, but then again, in some regard the particularly high CO_2 climate with glaciated poles that we are now approaching is different from any that has ever before held sway on the planet. If one is tugging on the dragon's tail with little notion of how much agitation is required to wake him, one must be prepared for the unexpected.

1. Clark, P. U., Webb, R. S. & Keigwin, L. D., eds. (1999) *Mechanisms of Global Change at Millennial Time Scales*, Geophysical Monography Series (Am. Geophys. Union, Washington, DC), Vol. 112.
2. Broecker, W. S. (1997) *Science* **278,** 1582–1588.
3. Macdonald, A. M. (1998) *Prog. Oceanogr.* **41,** 281–382.
4. Trenberth, K. E. & Solomon, A. (1994) *Clim. Dyn.* **10,** 107–134.
5. Talley, L. D. (1995) *Rev. Geophys.* **33,** 1335–1352.
6. Hendy, I. L. & Kennett, J. P. (1999) *Geology* **27,** 291–294.
7. Pierrehumbert, R. T. (1995) *J. Atmos. Sci.* **52,** 1784–1806.
8. Pierrehumbert, R. T. (1999) in *Mechanisms of Global Change at Millennial Time Scales*, Geophysical Monography Series eds. Clark, P. U., Webb, R. S. & Keigwin, L. D. (Am. Geophys. Union, Washington, DC), Vol. 112.
9. Pierrehumbert, R. T. (1998) *Geophys. Res. Lett.* **25,** 151–154.
10. Pierrehumbert, R. T. & Roca, R. (1998) *Geophys. Res. Lett.* **25,** 4537–4540.
11. Lindzen, R. S. & Hou, A. Y. (1988) *J. Atmos. Sci.* **45,** 2416–2427.
12. Thompson, L. G., Davis, M. E., Mosley-Thompson, E., Sowers, T. A., Henderson, K. A., Zagorodnov, V. S., Lin, P., Mikhalenko, V. N., Campen, R. K., Bolzan, J. F., *et al.* (1998) *Science* **282,** 1858–1864.
13. Miller, R. L. (1997) *J. Clim.* **10,** 409–440.
14. Cane, M. A. (1998) *Science* **282,** 59.
15. Trenberth, K. Y. & Hoar, T. J. (1996) *Geophys. Res. Lett.* **23,** 3057–3060.
16. Hughen, K. A., Schrag, D. P., Jacobsen, S. B. & Hantoro, W. (1999) *Geophys. Res. Lett.*, **26,** 3129–3132.
17. Guilderson, T. P. & Schrag, D. P. (1998) *Science* **281,** 240–243.
18. Gnanadesikan, A. (1999) *Science* **283,** 2077–2079.
19. Steig, E. J., Brook, E. J., White, J. W. C., Sucher, C. M., Bender, M. L., Lehman, S. J., Morse, D. L., Waddington, E. D. & Clow, G. D. (1998) *Science* **282,** 92–95.
20. Clement, A., Seager, R. & Cane, M. A. (1999) *Paleoceanography* **14,** 441–456.
21. Clement, A., Seager, R. & Cane, M. A. (1999) *Science*, in press.
22. Dijksra, H. A. & Neelin, J. D. (1995) *J. Clim.* **5,** 1344–1359.
23. Liu, Z. & Huang, B. (1997) *J. Clim.* **10,** 1662–1679.
24. Saravanan, R. (1993) *J. Atmos. Sci.* **50,** 1211–1227.
25. Battisti, D. S. & Ovens, D. D. (1995) *J. Atmos. Sci.* **52,** 3911–3931.