

Warm Oceans Raise Land Temperatures

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During 2004, sea surface temperatures (SSTs) were the third warmest in the past 125 years, land surface temperatures were the fourth warmest, and globally averaged temperatures likewise ranked fourth highest [Levinson, 2005]. This article presents evidence that SSTs contributed significantly to the widespread terrestrial and global tropospheric warmth.

Every ocean witnessed warm sea surface conditions in 2004, with only the middle latitudes of the Southern Ocean experiencing below average values (Figure 1, top). Much of this warmth was concentrated north of 30°S and included a weak El Niño event in the tropical central Pacific. Terrestrial warmth in 2004 was seen at all locations between 45°N and 45°S. The greatest departures from average temperatures occurred over interior Eurasia and western North America, which experienced increases of up to 2°C (Figure 1, middle). Consistent with the considerable warmth of ocean and land surfaces, much of the global troposphere was also warm in 2004. The thermal expansion of the tropospheric column, whose top is roughly at the 200-millibar pressure surface, is demonstrated by the increase in elevation of that surface worldwide (Figure 1, bottom).

The current analysis for 2004 illustrates a method of attribution research of climate conditions that can be more generally applied. It is recognized that land temperatures in recent years have consistently been above normal, with preliminary indications that 2005 was the warmest year for the globally averaged temperatures within the instrumental record. Results obtained for 2004 can be extended to explain similar warming for these other years. Furthermore, the usefulness of the methodology followed in this report could be easily adopted to analyze the global impact of SSTs on other meteorological variables of societal impact, such as rainfall.

The Ocean's Effect on the Tropospheric Warmth

Diagnosis of the ocean's contribution to global tropospheric warmth can be facilitated through the use of climate simulations subjected to the observed SSTs. Five different atmospheric general circulation models (AGCMs) were used in an analysis that formed part of an experimental suite spanning the latter half of the twentieth century and updated through 2004. An ensemble of experiments has been performed for each model in which identical SST evolutions have been specified, but the individual members differed in their atmospheric initial conditions (start dates were 1950).

A total of 81 simulations have been generated from these five models, whose basic characteristics are further detailed in Table 1 of Barnston *et al.* [2005].

The 2004 SSTs were of great consequence for global tropospheric warmth, according to the models. The AGCMs predict thermal

expansion of the troposphere at virtually all locations, as measured by an increasing elevation of the 200-millibar surface (Figure 2, bottom), consistent with the pervasive atmospheric warmth observed. The zonally averaged profile of this warm signal (Figure 2, right-hand plots) exhibits a distinctive tropical maximum, one that is qualitatively similar to that seen during El Niño years [Kumar and Hoerling, 2003].

Yet the amplitude of the 200-millibar height increases in the tropics is considerably greater than expected from weak El

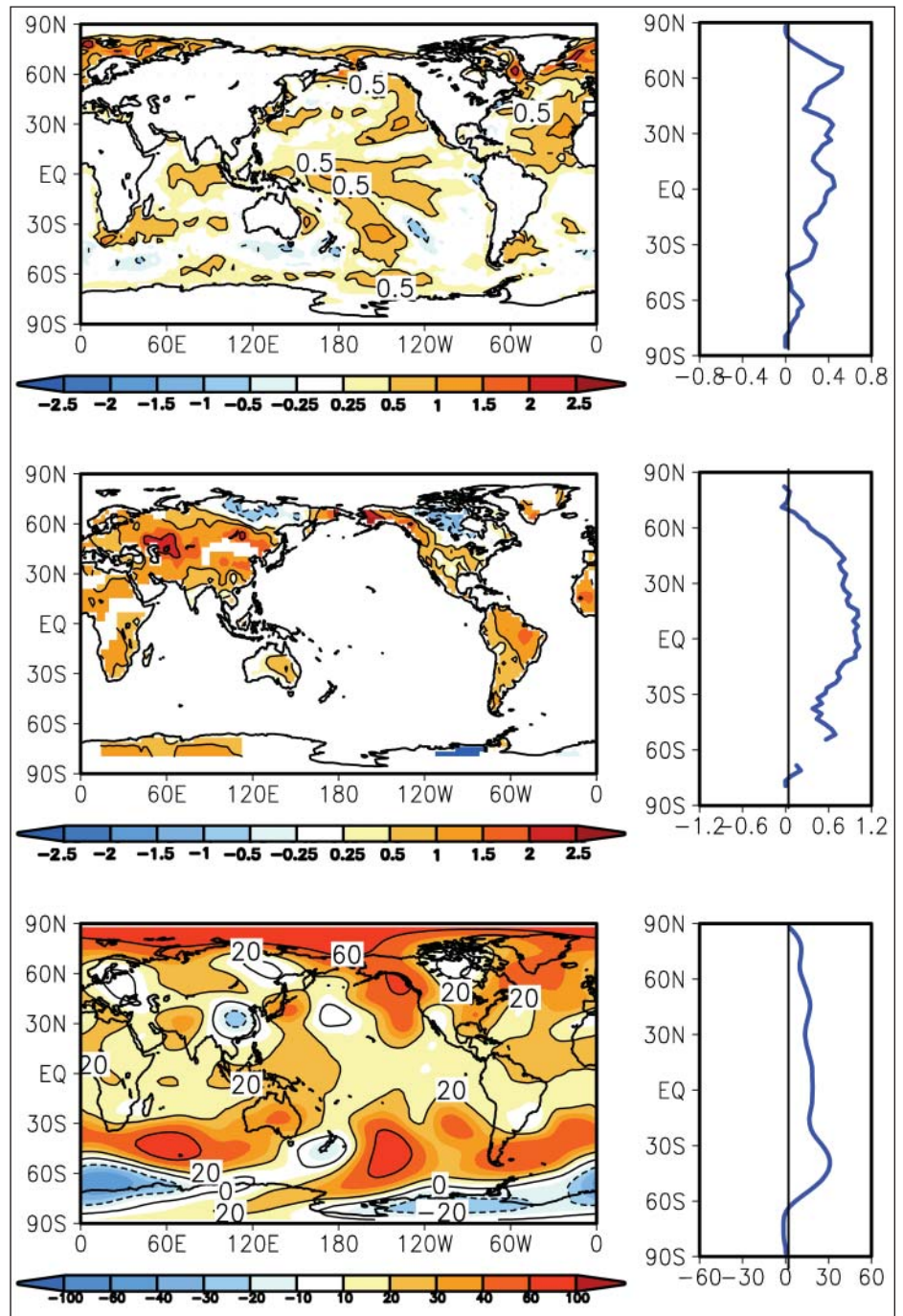


Fig. 1. The observed 2004 annually averaged (top) sea surface temperature anomalies (°C), (middle) land surface temperature anomalies (°C), and (bottom) 200-millibar geopotential height anomalies (meters). Curves in the right-hand panels are the zonally averaged values for (top to bottom) sea surface temperature, land surface temperature, and 200-millibar height anomalies. Reference period is 1961–1990.

Niño forcing [e.g., Kumar and Hoerling, 2003], suggesting a tropospheric warm response to additional, non-El Niño related warm tropical SST anomalies. In particular, the positive SST departures over the Indian Ocean and western Pacific coincide with the region experiencing a multidecadal warming trend [Knutson *et al.*, 1999]. Overall, while the pervasive tropical warming is realistically simulated, the larger than observed tropical 200-millibar height response of the models in 2004 is consistent with a bias toward greater interannual variability of such heights in these AGCMs.

The Ocean's Effect on Land Temperatures

Globally averaged land surface temperature departures for 2004 were computed for each of the 81 separate realizations. The ensemble-averaged AGCM land temperature signal for 2004 consists of pervasive warmth over Eurasia, Africa, Australia, South America, and most of North America (Figure 2, top). The North American warm signal is most prominent in the western and northern reaches of the continent. This overall warm response is remarkably similar to the observed 2004 terrestrial warmth, and furthermore every AGCM realization was found to have a warm response. This indicates that the sign of the 2004 land temperature anomaly was fully determined by the state of worldwide SSTs. The mean value of simulated warmth is $+0.6^{\circ}\text{C}$, close to the observed warm departure of $+0.8^{\circ}\text{C}$. As a measure of the uncertainty in this signal arising from model biases and atmospheric noise, the standard deviation among all 81 members was found to be 0.14°C .

In the AGCMs, the zonally (latitudinal) averaged land temperature signal is positive at all latitudes, as was observed, though the strength of that signal is about a factor of two weaker than the observed anomaly over the Northern Hemisphere extratropics. The robustness of the warm signal is confirmed by the fact that each model yields the same signed response of zonal mean land surface temperatures.

One conclusion drawn from this attribution exercise is that the observed terrestrial warmth of 2004 was entirely consistent with a global response to SSTs over the world's oceans. The fact that the oceans were the third warmest within the modern instrumental record was of great consequence to continental climates.

Multiple reenactments of the 2004 climate indicated that terrestrial temperatures could have differed in amplitude from those observed by chance alone. Therefore, it may have been pure coincidence that the observed $+0.8^{\circ}\text{C}$ land temperature departure of 2004 resided in the low probability state of the model simulations; the vast majority of runs produced weaker terrestrial warmth than observed with only two out of 81 exceeding the observed warmth. However, all of the AGCM simulations employed speci-

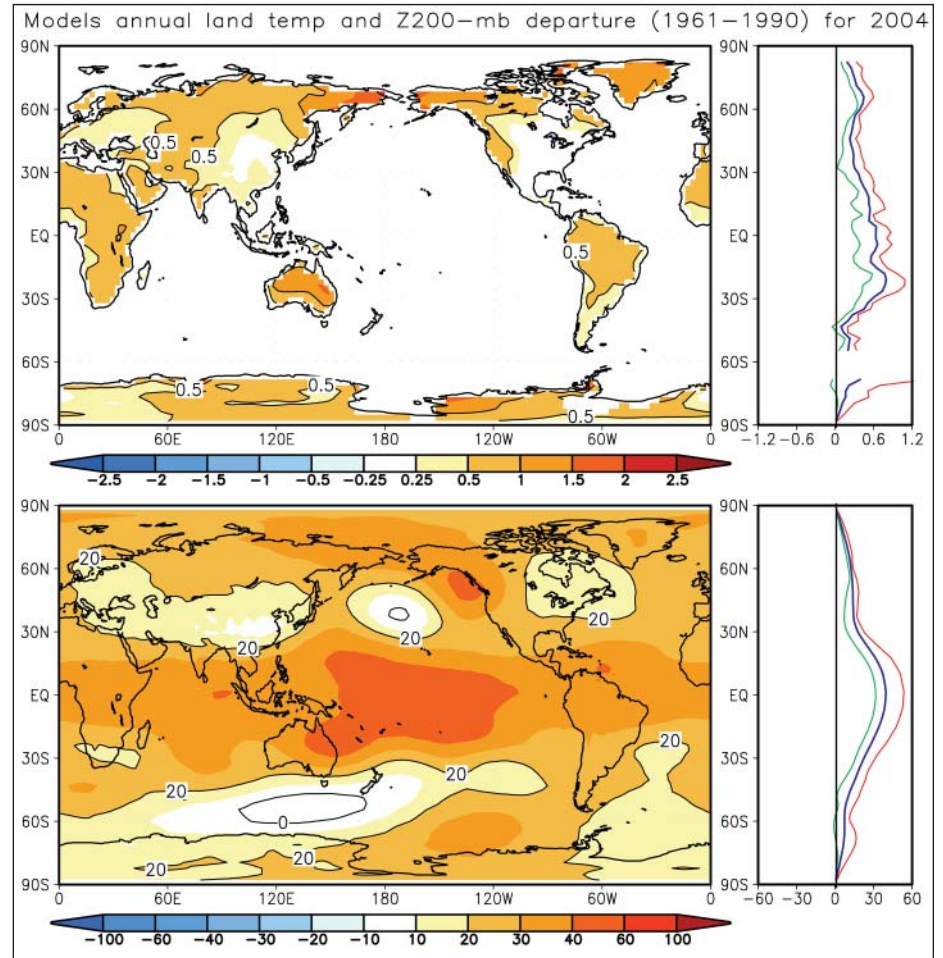


Fig. 2. The atmospheric general circulation model (AGCM) simulated 2004 annually averaged (top) land surface temperature anomalies ($^{\circ}\text{C}$) and (bottom) 200-millibar geopotential height anomalies (meters). Curves in the top and bottom right-hand panels are the zonally averaged land surface temperature and 200-millibar height anomalies, respectively. Extreme low (high) zonal mean values among the five AGCM ensembles are denoted by green (red) curves. The AGCMs have been forced with the observed 2004 sea surface temperature anomalies, and the ensemble average of 81 simulations from five AGCMs are shown. Reference period is 1961–1990 AGCM climatology.

fied atmospheric chemical compositions of trace gases. For example, carbon dioxide was assigned to twentieth-century climatological values corresponding roughly to 1980 conditions, a value roughly 10% less than the 380 ppm in 2004 [Levinson, 2005]. Thus, the experiments have not completely represented all the 'external forcings' that could have influenced terrestrial temperatures in 2004. It is reasonable to speculate that the direct radiative effect of increased trace gases in 2004 may also have contributed to terrestrial warmth.

Warming: Role of Anthropogenic and Natural Forcings

A further conclusion is that owing to the SST conditions, global terrestrial warmth was unavoidable during 2004. A central question then becomes the attribution for the SSTs themselves. Can, for example, pervasive ocean warmth in 2004 be attributed to greenhouse gas forcing? Previous efforts to explain trends in global SSTs in the latter

half of the twentieth century indicate that warming of the tropical Indo-Pacific warm pool (one of the conditions in 2004) is consistent with such forcing [Knutson *et al.*, 1999]. The SST warmth in all basins is consistent with elevated ocean heat content [Levitus *et al.*, 2005], the trend component of which has been attributed to increasing greenhouse gas forcing in coupled ocean-atmosphere model experiments [Barnett *et al.*, 2001; Levitus *et al.*, 2000]. These ocean heat content trends are themselves consistent with new evidence from satellite measurements that the Earth is now absorbing more energy from the Sun than it is emitting to space [Hansen *et al.*, 2005].

There are also indications that some of the SST warmth in 2004 was from natural causes, in particular, the El Niño being a phenomenon of unforced variability internal to the coupled ocean-atmosphere system. North Atlantic warmth has been prevalent since the late 1990s, and may also reflect in part a signal of natural multidecadal SST variability in that basin [e.g., Delworth and

Mann, 2000]. The relative contribution of natural variability and anthropogenic forcing to the warmth of 2004 SSTs will require analysis of ensemble multimodel coupled integrations with greenhouse gas, aerosol, and natural external forcings.

Providing assessments of the origin of climate states, and the role of specific forcings, is not only of great importance for understanding the role of natural and anthropogenic influences on climate, but is also expected to advance efforts on multiannual climate prediction. While having only explored the role of ocean surface conditions for terrestrial climate herein, the fact that such a large influence was isolated serves to further confirm the leading role of oceans in climate variability and change.

To the extent that natural origins for the SST states of 2004 were important, the simulations indicate that appreciable global mean land temperature variations can occur that may temporarily either enhance or mask anthropogenic signals of land temperature change. To the extent that greenhouse gas origins for the SST states of 2004 were

important, the simulations indicate that much of the global mean land warmth is (at least currently) arising from a feedback processes involving air-sea interactions. In either situation, anticipating the future trajectory of the oceans is argued to be of great significance for multiannual climate projections as a whole.

Acknowledgments

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Author Information

Martin P. Hoerling, Taiyi Xu, and Gary Bates, NOAA Climate Diagnostic Center, Boulder, Colo.; Arun Kumar and Bhaskar Jha, NOAA Climate Prediction Center, Washington, D.C.

NEWS

3-D Visualization of Tonga Earthquake

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Scientists at the Scripps Institution of Oceanography (SIO; La Jolla, Calif.) have created interactive three-dimensional (3-D) visualizations of the 3 May magnitude 8.0 earthquake that occurred near Neiafu, Tonga. The earthquake occurred at 1526 UTC at a depth of 16 kilometers (as recorded by the USArray seismic network operated at SIO, <http://anf.ucsd.edu>). A tsunami warning was initially issued, but it was subsequently canceled, and to date, no fatalities have been reported.

These 3-D visualizations are available for free download at the Scripps Visualization Center Web site (<http://www.siovizcenter>.

ucsd.edu). The first visualization shows the hypocenter of the 3 May Tonga main shock and locations of historical earthquakes. Global topography and bathymetry data are also included for reference. The second visualization shows a more localized view of the Tonga region, along with vertical cross sections of the velocity structure in the region. An obvious correlation can be seen between changes in the velocity structure and the historical earthquake locations, which map out the geometry of the Tonga subduction zone.

These visualizations were created with using the Fledermaus software developed by Interactive Visualization Systems and stored as a 'scene' file. To view these visualizations, viewers need to download and install the

free viewer program iView3D (<http://www.ivs3d.com/products/iview3d>). Viewers can then explore the scene file by rotating, zooming in and out, or panning over the data. They can use the left mouse button to spin the data; click and drag the middle mouse button to zoom in and out of the center of the screen; and click and drag the right mouse button to zoom in on a specific point of interest. For detailed instructions, viewers can refer to the Help menu after launching iView3D.

This visualization work was made possible by U.S. National Science Foundation award EAR-0545250 to SIO, University of California, San Diego for "Community Access to Visualizations of EarthScope Focus Sites: Collaborative Construction of Virtual 3-D Models."

—DEBI KILB, ALLISON JACOBS, ATUL NAYAK, AND GRAHAM KENT, SIO, University of California, San Diego; E-mail: anayak@ucsd.edu

Source of Climate Change Becomes Focus of Senate Hearing

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A 26 April Senate subcommittee hearing on the possible effects of climate change developed into a discussion about the extent to which the climate warming can be explained by natural or anthropogenic causes.

The hearing before the Senate Commerce, Science, and Transportation Subcommittee on Global Climate Change and Impacts began with subcommittee chair Sen. David Vitter (R-La.) acknowledging that the planet is experiencing a warming trend and that understanding the potential changes that

may accompany the warming is an important task. "For once, we are not here to argue about the causes of observed warming trends," he said.

Steve Murawski, director of Scientific Programs and chief science advisor for the National Marine Fisheries Service, spoke about several possible effects of climate change, including a long-term rise in sea levels, increasing acidification of the oceans, loss of sea ice, and rising water temperatures.

Thomas Armstrong, director of the Earth Surface Dynamics Program at the U.S. Geological Survey, brought up the question of

what is the cause of climate change. Armstrong noted that the scientific community is largely in agreement that human activity in the twentieth and twenty-first centuries has enhanced greenhouse gas concentrations in the atmosphere and affected global temperature and climate.

"But climate change is also a natural, continuous, inevitable Earth process that has occurred throughout Earth's history," Armstrong said. Understanding the processes and distinguishing natural change from change imposed on the natural system by human activities "is just the first step towards success in the field of climate change," he told the subcommittee.

These statements prompted questions from Sen. Vitter on how twentieth-century