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The impact of aerosols on simulated ocean temperature and heat content in the 20th century

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[1] Observational analyses have documented increases in global ocean temperature, heat content, and sea level in the 20th century. Previous studies argued that the observed ocean warming is a response to increasing greenhouse gases. We use a new climate model to decompose simulated ocean temperature changes into components attributable to subsets of anthropogenic and natural influences. The model simulates a positive trend in global ocean volume mean temperature from the mid 1950s to 2000, consistent with observational estimates. We show that for the period 1861–2000 aerosols have delayed the onset of ocean warming by several decades and reduced the magnitude of the transient warming by approximately two-thirds when compared to the response that arises solely from increasing greenhouse gases. The simulated cooling signature from large volcanic eruptions in the late 19th and early 20th centuries is clearly visible in the subsurface ocean well into the middle part of the 20th century. **Citation:** Delworth, T. L., V. Ramaswamy, and G. L. Stenchikov (2005), The impact of aerosols on simulated ocean temperature and heat content in the 20th century, *Geophys. Res. Lett.*, *32*, L24709, doi:10.1029/2005GL024457.

1. Introduction

[2] The global ocean, with its extremely large effective heat capacity, is the dominant reservoir for storing heat gained or lost by the Earth's climate system [*Levitus et al.*, 2001]. Previous observational analyses have documented increases in global ocean volume mean temperature [*Levitus et al.*, 2001, 2005; *Willis et al.*, 2004] and sea level [*Church et al.*, 2001; *Cazenave and Nerem*, 2004] over the last several decades. Modeling studies [*Levitus et al.*, 2001; *Barnett et al.*, 2001, 2005; *Reichert et al.*, 2002; *Crowley et al.*, 2003] have shown that the observed increase in oceanic heat content is largely attributable to human activity via increasing greenhouse gases. Further, such changes in global ocean heat content have been used to estimate the net radiative imbalance of the Earth's climate system [*Hansen et al.*, 2005].

[3] While recent work has focused on the upward trend in observed global ocean heat content and its relationship to anthropogenic forcing, an important question is "What are the roles of the differing types of radiative forcing agents in producing the observed global ocean warming?". In this study we decompose simulated ocean heat content changes into components associated with various natural and anthropogenic climate change forcing agents. We show that over the 20th century anthropogenic aerosols appear to have played a major role in offsetting – at least temporarily - the increases in global ocean volume mean temperature and sea level arising from well-mixed greenhouses gases, with a smaller but nonetheless significant role for volcanic aerosols. Globally-averaged volume mean ocean temperature can be a sensitive indicator of climate change, since this represents a time and space integral of the net surface energy balance. Consistent with this, we show that the simulated cooling signature from large volcanic eruptions in the late 19th and 20th centuries is clearly visible in the subsurface ocean well into the mid-20th century.

2. Methods

[4] Using a newly developed global coupled ocean-atmosphere model [*Delworth et al.*, 2005], a five member ensemble of experiments was conducted for the period 1861–2000 forced with a comprehensive set of time-varying radiative forcing agents. These included observational estimates of changes in well-mixed greenhouse gases, land use, solar irradiance, and volcanic aerosols. Also incorporated were changes in tropospheric and stratospheric ozone, as well as tropospheric and stratospheric aerosols (direct effect only), using estimates based on the output of a chemical transport model forced with observed emissions estimates. This ensemble is referred to as "ALL". Additional three member ensembles were conducted over the period 1861–2000 using subsets of the changes in radiative forcing agents. These are denoted as: "ANTHRO" (all anthropogenic terms), "NATURAL" (volcanic and solar changes), "WMGGO3" (well-mixed greenhouse gases plus stratospheric ozone), and "AEROSOL" (anthropogenic aerosols). We calculate the response of the climate system as the ensemble mean minus the corresponding segments of a long control run, in which the climate forcing agents are held fixed at 1860 levels. Additional details of the model formulation and experimental design are given by *Knutson et al.* [2005] and in the auxiliary material[1].

3. Results

[5] We show in Figure 1 the time series of global ocean volume mean temperature and heat content from the various experiments. The black line denotes the results from "ALL", and reveals clear warming of the global ocean over most of the 20th century, with an increased rate of warming

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[1] Auxiliary material is available at ftp://ftp.agu.org/apend/gl/2005GL024457.

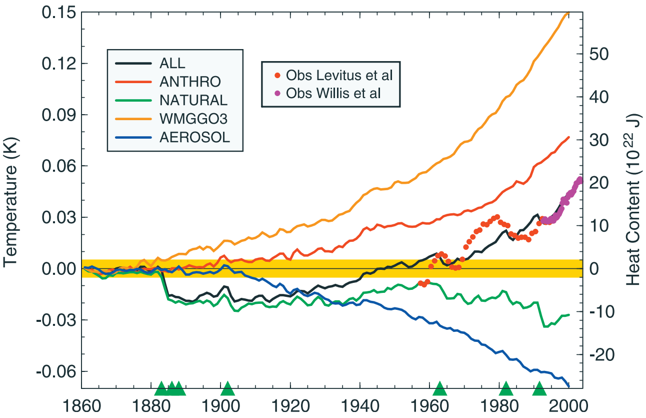

Figure 1. Time series of global mean ocean temperature (0–3000 m, scale on left vertical axis) for experiments as indicated in the legend (the 0–3000 m depth range was chose for comparison to observational estimates [*Levitus et al.*, 2005]; the primary results are not sensitive to this choice). The values are expressed as ocean heat content on the right vertical axis. The upper and lower limits of the yellow shaded region denote plus and minus two standard deviations of ocean temperature as calculated from CONTROL (after filtering to remove multi-century drift). The red circles denote an observational estimate of ocean heat content from *Levitus et al.* [2005] over the 0–3000 m. layer (referenced to right vertical axis). The purple circles denote observational estimates of heat content over the 0–750 m. layer from *Willis et al.* [2004] (referenced to right vertical axis). To facilitate comparisons between the simulated and observed data, constant offsets were added to the observed data so that their means were the same as the model data over the period of overlap (since heat content values are only meaningful as differences, arbitrary constant offsets can be added). The green triangles along the bottom denote the times of major volcanic eruptions.

in the last several decades. The simulated late 20th century trend in ocean heat content is in excellent agreement with recent estimates [*Willis et al.*, 2004], and is quantitatively consistent with the longer term trend derived from in situ measurements [*Levitus et al.*, 2005]. The simulated decadal scale variability is smaller in amplitude than in observational estimates; it has been suggested [*Gregory et al.*, 2004; *AchutaRao et al.*, 2005] that this difference is related to the relatively limited observational network.

[6] There are notable downward jumps in the model time series. These are associated with major volcanic events [*Crowley et al.*, 2003], which increase the reflection of solar radiation back to space. This creates a negative surface radiative balance over the ocean, resulting in a global ocean cooling. Thus, the sharp downward spike in the early 1880s follows the eruption of Krakatau (August, 1883); similarly, the downward spikes in the latter half of the 20th century follow the eruptions of Mts. Agung, El Chichon, and Pinatubo in 1963, 1982, and 1991 respectively. The impact of volcanic eruptions on ocean heat content is seen in other models as well [*Church et al.*, 2005; P. J. Gleckler et al., Century scale effects of volcanic eruptions, submitted to *Nature,* 2005].

[7] Although the direct impact of volcanoes on the surface energy balance and surface air temperature lasts only a few years [*Knutson et al.*, 2005], the impact on simulated global ocean temperature persists for decades. This is seen clearly from the green curve in Figure 1, showing global ocean temperature from ensemble "NATURAL". The negative departures of global ocean temperatures induced by the eruptions of Krakatau (1883) and Santa Maria (1902) persist for many decades; in fact, the ocean temperature in this ensemble never returns to its initial value, indicating that the net effect of the volcanic plus solar forcing is a net cooling. While the negative subsurface temperature anomalies originating from late 19th and early 20th century volcanic activity have diminished somewhat by the middle of the 20th century, the late 20th century volcanic eruptions reinforce the subsurface cooling.

[8] An essential feature of global ocean heat content is that a negative (positive) departure of the planetary net radiative balance away from a balanced state (i.e., one in which downward and upward net energy fluxes at the surface are approximately equal) will result in a cooling (warming) of the global ocean. The cooled (or warmed) state persists until an energy imbalance equal in its time-integrated impact on the surface energy balance (but opposite in sign) occurs. The oceanic signature of cooling from relatively short-lived surface radiative imbalances (such as volcanic eruptions) may persist long after the climate system has returned to a balanced state. Although the surface temperature a few years after a volcanic event may return to the state before the eruption, the subsurface cooled waters persist for decades.

[9] We show the differing roles of natural and anthropogenic forcings on global ocean temperature by contrasting the green (NATURAL) and red (ANTHRO) curves. It is apparent that natural forcings (primarily volcanic eruptions) have offset a substantial portion of the anthropogenic warming of the world ocean in the late 19th and 20th centuries. Solar irradiance changes (mainly the increase in the early 20th century) have contributed to the ocean warming, but appear to be smaller in their integrated effect than the volcanic contributions.

[10] The influence on global ocean temperature of differing types of anthropogenic forcings (anthropogenic aerosols versus well-mixed greenhouse gases, including stratospheric ozone) is shown by contrasting the blue (AEROSOL) and orange (WMGGO3) curves in Figure 1. Anthropogenic aerosols have increased over the past 50 years [*Ramaswamy et al.*, 2001], and in our simulations they have offset – at least temporarily - approximately half of the global ocean warming that is caused by increases in well-mixed greenhouse gases alone.

[11] The vertical structure of the ocean temperature changes is shown in Figure 2 for the ALL, NATURAL, and ANTHRO ensembles. Starting in the top panel with ALL, two main features are evident: first, there is a warming of the global ocean, occurring mainly in the latter part of the 20th century. Secondly, the subsurface expression of the Krakatau eruption is clear. The blue shading near the surface in the 1880s and 1890s indicates the cooled water resulting from the negative planetary radiative balances induced by Krakatau (1883) and succeeding eruptions (Tarawera, 1886; Bandai, 1888; Santa Maria, 1902). The simulated net flux of heat into the ocean, averaged over the world ocean, was reduced by a

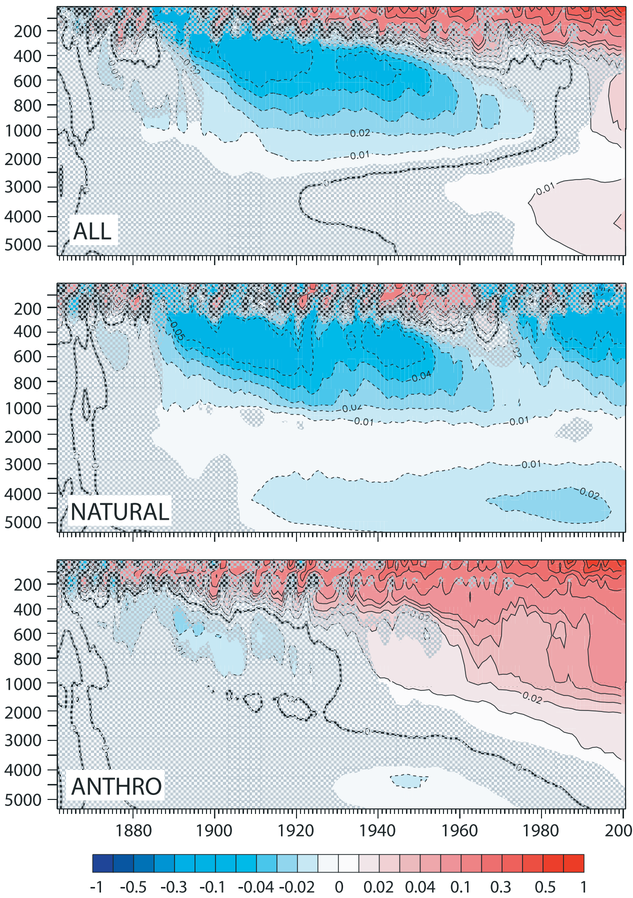

Figure 2. Time-depth plot of global mean temperature calculated as the ensemble mean of the perturbation experiments minus the control integration; the values plotted are departures from the 1861–1870 time-mean. Units are K. Note the differing scaling on the vertical axis above and below 1000 m. Stippled (non-stippled) areas indicate anomalies less (greater) than two standard deviations. The standard deviations were calculated from CONTROL, after filtering to remove multi-century drift. Contour levels are non-linear, with intervals of 0.01 between −0.05 and 0.05, 0.1 between −0.5 and −0.1, and 0.1 to 0.5, and 0.25 for absolute values greater than 0.5. (top) Ensemble ALL. (middle) Ensemble NATURAL. (bottom) Ensemble ANTHRO.

time-mean over the period 1883–1885 of 2.1 W m^{-2} (peak value of 3.7 W m^{-2} in 1884). This imbalance cools surface waters, which gradually penetrate into the subsurface ocean. Their signature is clearly visible well into the 20th century, long after the surface manifestations of Krakatau are gone [*Knutson et al.*, 2005]. These results highlight the multi-decadal persistence of subsurface ocean temperature anomalies. In the absence of direct contact with the atmosphere, where air-sea fluxes are strong, the damping of subsurface anomalies is weak and their persistence can be quite long.

[12] It should be noted that there is uncertainty regarding the aerosol forcing associated with volcanic eruptions, particularly those as long ago as Krakatau. The specified aerosol changes for Krakatau are somewhat larger than those specified for Pinatubo, which has considerably more observational basis.

[13] The subsurface volcanic signature is perhaps even clearer in the middle panel, which shows the results from the NATURAL ensemble. The negative temperature anomalies induced by Krakatau persist well into the 20th century; indeed, they are still present when the eruptions of Mts. Agung, El Chichon, and Pinatubo occur in 1963, 1982, and 1991 respectively. These latter volcanic eruptions cool the surface again, and reinforce the subsurface negative temperature anomalies.

[14] In contrast to the top two panels, ensemble ANTHRO presents a picture of steadier warming. Notably, the subsurface ocean warms several decades earlier in ANTHRO than ALL, indicating the impact of volcanic eruptions in delaying anthropogenic warming of the world ocean.

[15] The subsurface evolution of temperature in ensembles AEROSOL and WMGGO3 is shown in Figure 3. Consistent with the curves in Figure 1, both panels show rather monotonic trends of global ocean temperature. In ensemble WMGGO3 the warming signal penetrates to 1000 m early in the 20th century, in contrast to ANTHRO and ALL where the warming signal penetrates to 1000 m in the 1940s and 1990s respectively. An interesting feature is that in the simulations with aerosol forcing the significant temperature signals (using anomalies greater than two standard deviations as an indicator of significance) appear much earlier in the subsurface than in the near-surface layers. A cooling signal penetrates vertically in the ocean more easily than a warming signal by decreasing the vertical stability of the water column. It could be noted that aerosols have a very direct and immediate impact on the ocean surface through changes in the net surface shortwave radiation.

4. Discussion

[16] Over the last several years changes in global ocean temperature and heat content have emerged as a powerful

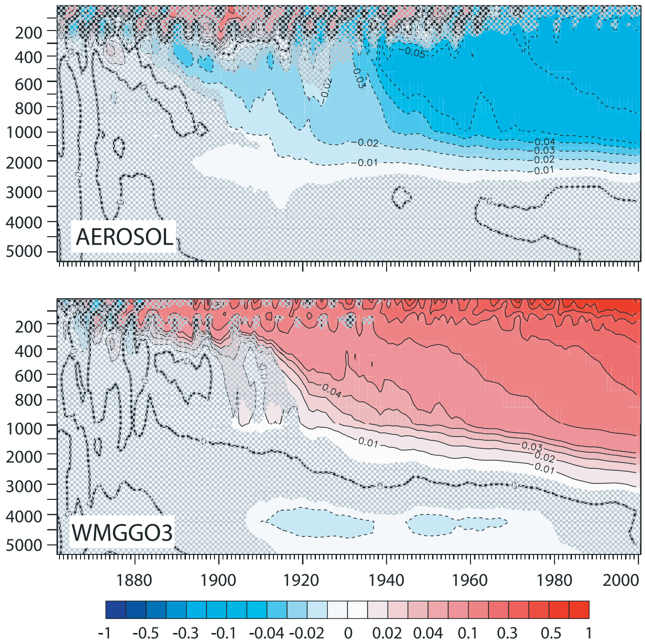

Figure 3. Same as Figure 2, except using ensembles (top) AEROSOL and (bottom) WMGGO3.

indicator of the signature of radiatively forced climate change. The ocean acts as a temporal integrator of net planetary radiative imbalances, and thus the time series of ocean heat content has the appearance of a low-pass filtered signal. This differs somewhat from surface air temperature, which responds more rapidly to radiative forcing changes.

[17] An important implication of this work is that natural and anthropogenic aerosols have substantially delayed and lessened the total amount of global ocean warming – and therefore of sea level rise – that would have arisen purely in response to increasing greenhouse gases. The short residence time of aerosols in the atmosphere suggests that this situation could change relatively rapidly.

[18] Quantitatively, anthropogenic aerosols have reduced the ocean warming simulated in our model by approximately half over the period 1861–2000 when compared to the warming that occurs solely in response to increasing greenhouse gases. When the effects of volcanic aerosols are included, the simulated ocean warming in our model is reduced by approximately two-thirds. Such quantitative estimates of the impact of aerosols must be viewed in light of the uncertainties in our understanding of aerosol forcing, but there is considerable evidence that aerosol concentrations have substantially increased in the latter half of the 20th century [*Ramaswamy et al.*, 2001].

[19] We can express this warming as a sea level change attributable to expansion of the water column due to density reductions, using the same method as *Gregory and Lowe* [2000] (the density reductions come primarily from ocean warming, consistent with *Antonov et al.* [2002]). Expressed this way, aerosols have reduced – at least temporarily - the simulated increase in sea level over the period 1861–2000 from approximately 7 cm to 2.4 cm (this excludes any effects on sea level due to changes in continental ice). These results demonstrate the profound role that aerosols – both natural and anthropogenic – appear to play in multi-decadal to centennial scale changes of sea level.

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