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# Modeling ocean heat content changes during the last millennium

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[1] Observational studies show a significant increase in ocean heat content over the last half century. Herein we estimate heat content changes during the last millennium with a climate model whose forcing terms have been best-fit to surface proxy data. The model simulates the observed late 20th century ocean heat content increase and a comparable Little Ice Age minimum. When glacial advances are factored in, these results imply a sea level fall after the Middle Ages that is consistent with some geologic data. The present ocean heat content increase can be traced back to the mid-19th century, with a near-linear rate of change during the 20th century. *INDEX TERMS:* 0370 Atmospheric Composition and Structure: Volcanic effects (8409); 1620 Global Change: Climate dynamics (3309); 1635 Global Change: Oceans (4203); 4556 Oceanography: Physical: Sea level variations. **Citation:** Crowley, T. J., S. K. Baum, K.-Y. Kim, G. C. Hegerl, and W. T. Hyde, Modeling ocean heat content changes during the last millennium, *Geophys. Res. Lett.*, *30*(18), 1932, doi:10.1029/2003GL017801, 2003.

## 1. Introduction

[2] Assessments of climate change provide increasing support for the importance of anthropogenic greenhouse gas changes in explaining the late 20th century surface temperature increase. Recently, surface temperature observations have been augmented by ocean temperature profile data [*Levitus et al.*, 2000] indicating a significant increase in ocean heat content from 1955–1996. Model results [*Barnett et al.*, 2001; *Levitus et al.*, 2001] suggest that such an increase can only be explained by greenhouse gas increases. Parallel to these developments, paleoclimate modeling studies [*Robock*, 1979; *Free and Robock*, 1999; *Crowley*, 2000] indicate a significant role for naturally forced climate variability over the last millennium. Herein we combine these two strands of research to assess how the magnitude of observed changes in ocean heat content compares with model predictions of the forced response over the last 1,000 years.

[3] In order to avoid an arbitrary tuning of a climate model to observed heat content changes, our strategy is to first use an ensemble of simulations over the last six hundred years (where the forcing is best known) to determine model parameters that provide a best-fit simulation of surface temperatures. We then extend the best-fit calculation back to A.D. 1000 and compare its ocean heat content with observations. First, we discuss the climate model, forcing, and proxy data.

## 2. Model and Forcing Terms

[4] Although it is now feasible to perform some general circulation model (GCM) simulations of century-scale duration, we need to test a wide range of parameter space that can only reasonably be examined with simpler energy balance models (EBMs), which reproduce many of the large-scale temperature responses of GCMs [*Crowley et al.*, 1991]. Previous EBM simulations [*Free and Robock*, 1999; *Crowley*, 2000] compared results with hemispheric scale temperature reconstructions [*Mann et al.*, 1999; *Crowley and Lowery*, 2000]. Since most paleoclimate data are from the mid- and high-latitudes of the northern hemisphere, in this study we employ a linear North-type [*North et al.*, 1983] 2D (i.e., realistic land-sea distribution) seasonal model to compare the model results over the same domain as the data.

[5] The EBM has an upwelling-diffusion deep ocean coupling that allows for heat content changes in the ocean interior. This is a standard approach with simple models [*Wigley and Raper*, 1987] to simulate heat content changes and continues to be used in the recent Intergovernmental Panel for Climate Change projections. Vertical diffusivity was varied over a range of 1.2–2.4 $cm^2/s$.

[6] The model is driven by external forcing changes in greenhouse gases, solar irradiance, volcanism, and tropospheric aerosols. Two of the forcing field fields used in the present study are from *Crowley* [2000]—pre-1850 greenhouse gas changes are based on ice cores and a recent summary over the instrumental interval, and solar irradiance is based on a $^{10}Be$ ice core record spliced into the *Lean et al.* [1995] reconstruction after 1600. Tropospheric aerosol forcing (i.e., direct plus indirect) ranges from 0.3–1.0 $W/m^2$ for 30–90°N; there is a latitudinal taper to lower values in the other equal-area strips (0–30°N, 0–30°S, 30–90°S).

[7] The volcano forcing time series from *Crowley* [2000] has been updated to include global forcing. In addition to data from the GISP2 [*Zielinski*, 1995] and Crete ice cores [*Hammer et al.*, 1980], we compiled results from other assessments of northern hemisphere volcanism [*Robock and Free*, 1996] through 1960 (the less complete ice core information and dispersion of volcano signals in the snow and firn layer make estimates after that time more difficult). Greenland signals were compared to Antarctic ice core data and composites to infer cases of global scale volcanism [*Moore et al.*, 1991; *Delmas et al.*, 1992; *Langway et al.*, 1995; *Cole-Dai et al.*, 1997; *Crowley et al.*, 1997; *Robock and Free*, 1996].

[8] Ice core peaks in sulphate/conductivity were initially scaled against the 1883 Krakatau eruption in each core.

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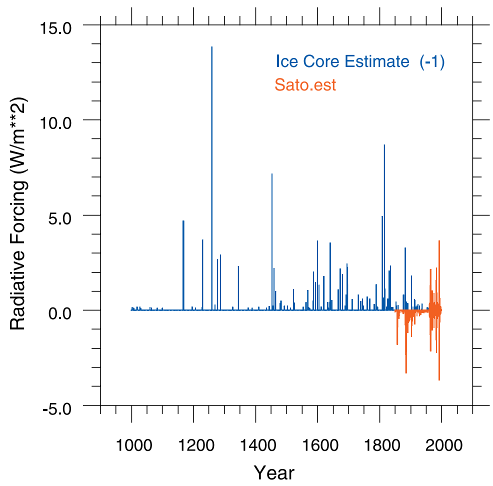


**Figure 1.** Estimated radiative forcing changes from global volcanism derived from ice core measurements (blue) and ground-based aerosol optical depth (red) measurements converted to radiative forcing as discussed in *Sato et al.* [1993] and text. Note that (−1) refers to the global ice core record multiplied by −1 for display purposes.

Because there is considerable uncertainty about the absolute value of Krakatau aerosol optical depth (AOD) estimates, the preliminary ice core scaling for 1900–1960 was validated against the presumably more-reliable 30–90°N 1900–1960 portion of the AOD record with a total least squares fit. Adjustments were made to the time series to bring the validation fit to a slope of 1.0. The AOD was converted to radiative forcing using a factor of 30 multiplier [*Sato et al.*, 1993] determined by radiative convective modeling.

[9] Subsequent to the AOD scaling, a volcano catalog [*Simkin and Siebert*, 1994] was used to assign tentative sources to many of the eruptions. Unknown ice core peaks were assigned a high latitude (>60°) origin unless they could be verified in ice cores from both hemispheres; this approach minimizes the effects of ice core volcano peaks unless their larger-scale imprint can be verified with independent data. The new reconstruction of global volcanism (Figure 1) indicates particularly low levels of volcanism in most in the 11th and 12th centuries and higher levels of the 13th century, ~1580–1700, and the early 19th and late 20th centuries. The mid-20th century decrease in AOD can also be found in other ice core time series.

[10] In order to compare the model with observations we updated the *Crowley and Lowery* [2000] reconstruction by dropping low resolution records and time series that had a low correlation with temperature, and restricted the analysis to 30–90°N, where almost all long paleo-time series are located. As we wanted to ensure that no temporal trends are an artifact of increasing data density in the younger intervals, we chose this reconstruction as a starting point because it is based only on long records that are time-invariant between 1078–1960 (one record drops out between 1000–1078).

[11] The following long proxy indices from the Crowley-Lowery composite were used (see that paper for full information on sites): tree ring records from the White Mtns. of California, Alberta, Canada, northern Sweden, the Ural Mtns., the Taimyr Peninsula of Siberia, and a record from southern France. We also used the GISP2 ice core from central Greenland, the Dunde ice core on the Tibetan Plateau, and a historical record of sea ice fluctuations around Iceland. The paleotemperature estimate is based on a weighted mean of the local records, with weights determined by the regression coefficients of individual records with the decadally smoothed 1856–1960 portion of the 30–90°N instrumental record [*Jones et al.*, 1999; *Hegerl et al.*, 2003].

## 3. Results and Discussion

[12] As discussed in *Hegerl et al.* [2003], the best fit from an ensemble of 120 simulations involved a sensitivity of 2.5°C, a vertical diffusivity of 2.4 $cm^2/s$, and a 30–90°N tropospheric aerosol forcing of 0.7 $W/m^2$, and explained 77% of the decadal scale variance from 1400–1960, and 57% of the variance over the interval 1000–1960 (Figure 2). Over the 1400–1960 interval *Hegerl et al.* [2003] also determined that the model could explain 49–67% of the decadal variance in three other paleo-reconstructions [*Mann et al.*, 1999; *Briffa et al.*, 2001; *Esper et al.*, 2002], but the amplitude of the response varied by time series (see further comments below).

[13] The best-fit model simulations (Figure 3) result in an ocean heat content change between 1955–1996 of ~1.75 $\times 10^{23}$ Joules for 0–3000 m, which is in very good agreement with *Levitus et al.* [2000]. For the paleo part of the record, the model simulates a decrease in ocean heat content after the Middle Ages that is consistent with some spot reconstructions of centennial scale sea level variations based on paleo-data [*Tanner*, 1992; *van de Plassche et al.*, 1998]. Because the deep ocean has a long time constant

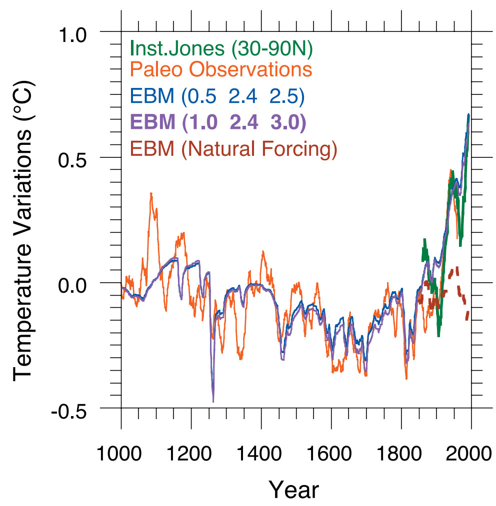


**Figure 2.** Best fit between model and surface proxy data. Comparison is for decadally smoothed EBM best fit simulations of temperature change over the last millennium with proxy reconstruction and decadally smoothed 30–90°N instrumental record. The 20th century response to natural forcing is also shown. In this and other figures the 0.0°C reference line refers to the expected value if there were no solar, greenhouse, or volcanic forcing from 1000–1850. The abbreviations for the EBM runs refer to parameters used for a particular run (e.g., 0.5, 2.4, 2.5 refers to a tropospheric forcing for 30–90°N of 0.5 $W/m^2$, ocean vertical diffusivity of 2.4 $cm^2/s$, and equilibrium climate sensitivity for a doubling of $CO_2$ of 2.5°C).

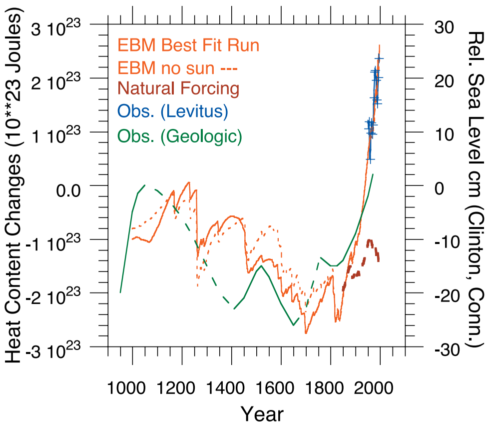


**Figure 3.** Simulated ocean heat content change over the last millennium for best-fit "surface" run of and a second run at 3.0°C sensitivity but without solar forcing (see text). The simulation for (1.0, 2.0, 3.0; see Figure 2) is similar and was not plotted in order to preserve clarity. Both runs were started at 1 A.D. in order to allow the system to adjust to the radiative forcing perturbations (see text). The 20th century response to natural forcing is shown for reference. Also shown are the ocean heat content values from *Levitus et al.* [2000] and an estimate of relative sea level changes from marsh deposits near Clinton, Connecticut [*van de Plassche et al.*, 1998]. Dashed lines refer to intervals of no deposition or erosion; sea level changes during this time are inferred from surrounding intervals of preserved sediment (solid lines).

[*Hansen et al.*, 1985], our Medieval ocean heat content values are sensitive to the initial state at A.D. 1000. We therefore illustrate the evolution of heat content after A.D. 1000 for a simulation that starts at A.D. 1, using zero forcing from A.D. 1–999 for all terms but volcanism and a constant "volcanic" forcing of $-0.15$ W/m$^2$/yr (this value is slightly less than the mean of the second millennium volcanism that *Zielinski* [1995] has charcterized as having high levels of activity). In this way we allow the model at A.D. 1000 to be in approximate equilibrium with the prescribed, but more uncertain, volcanic forcing from A.D 1–999. This exercise indicated that the the adjustment time for ocean heat content changes in the model is on the order of 400 years (Figure 4).

[14] Subsequent to the Little Ice Age minimum from about 1600–1840, the model simulates an ocean heat content rise of $\sim$5.0 $\times$ $10^{23}$ Joules. This rise is almost a factor of three greater than the heat content increase recorded in the interval overlapping the *Levitus et al.* [2000] data set and, when compared to the rise predicted by natural forcing, can almost entirely be attributed to greenhouse gas forcing. The absolute value of the heat content maximum is comparable to the minimum in the Little Ice Age. A linear fit to the 20th century part of the simulation explains 98.8% of the variance - a result consistent with tide gauge assessments [*Church and Gregory*, 2001] indicating that there is no clear evidence for an acceleration of sea level rise in the 20th century. However, annual values in the 1990s are above the long-term growth rate, increasing by $\sim$0.1 $\times$ $10^{23}$ Joules/yr. after the three-year dip following the 1991 Pinatubo eruption.

[15] Assessment of the roles of individual forcing (Figure 4) indicates that both tropospheric and volcanic aerosol forcing increased in the latter half of the 20th century, thereby "flattening out" by chance the exponential rate of increase due to greenhouse gases. During the first half of the 20th century, when volcanism and tropospheric aerosols were low, the increase in greenhouse gases accounts for 80% of the simulated 1.6 $\times$ $10^{23}$ Joule increase in ocean heat content—a value almost as large as the simulated late 20th century increase. Comparison with the response from "natural" forcing (Figure 4) underlines this conclusion - our results indicate that most of the 20th century heat content increase is driven by greenhouse gas forcing.

[16] Because there are continued uncertainties about the reality of past solar irradiance changes [*Lean et al.*, 2002], we also illustrate a run without solar forcing but with climate sensitivity increased 20% to compensate for the reduced solar forcing in the 20th century [cf. *Crowley and Kim*, 1999]. We get a comparable increase in ocean heat content through the 20th century. Even though the best fit diffusivity is 2.4 cm$^2$/s, we also examined runs with diffusivity of 1.2 cm$^2$/s because their residuals were only slightly larger than the best fit case. For a sensitivity of 3.0°C, we found a 1.4 $\times$ $10^{23}$ Joule increase—slightly less than Levitus et al. but within the uncertainty of the observations.

[17] The decrease in total ocean heat content in the Little Ice Age, and subsequent increase since the mid-19th century, has implications in a number of areas. Using the relationship developed in *Wigley and Raper* [1987], the change in ocean heat content since $\sim$1840 would be associated with about a 7 cm rise in sea level. Changes in glacier mass balance [*Church and Gregory*, 2001] would account for about 4 cm more. These results might explain the "early" rise is sea level observed in some tide gauge records [*Church and Gregory*, 2001]. However, the sea level record still has a $\sim$50% larger amplitude than calculated [cf. *Munk*, 2002].

[18] The heat content decrease during the Little Ice Age also suggests that certain parts of the ocean interior, such as the relatively young waters of the Atlantic Basin, may have

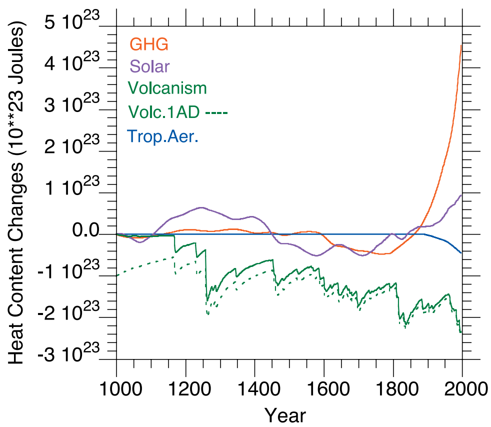


**Figure 4.** Simulated ocean heat content changes over the last millennium for individual forcing runs. See Figure 2 caption for discussion of reference level. Dashed line refers to volcanic forcing run beginning at A.D. 1000, solid line volcanic forcing beginning at A.D. 1 (see text).

temperatures cooler than predicted by models using present atmospheric forcing levels. This result has implications not only for validation of ocean models but also suggests that deconvolution techniques could conceivably back out the Little Ice Age temperature signal from existing hydrographic data.

[19] Although there is good agreement between our model and a variety of data, the absolute value of Little Ice Age ocean heat content changes are open to a number of uncertainties. Other volcanic reconstructions [e.g., *Robertson et al.*, 2001] suggest larger forcing than used in our time series. This would not necessarily translate into a larger heat content change because the best fit between model and data would then lead to a smaller sensitivity, yielding (we conjecture) comparable levels of Little Ice Age ocean heat content reductions for the same paleo reconstruction. However, best surface fits to other paleo reconstructions could yield different heat content changes back through time. For example, *Hegerl et al.* [2003] obtain smaller best fit sensitivities for the *Mann et al.* [1999] and *Briffa et al.* [2001] reconstructions, and larger best fit sensitivity to the *Esper et al.* [2002] reconstruction [cf. *Pollack and Huang*, 2000]. For these cases we would expect different magnitudes of change through time, including the late 20th century. Sensitivity experiments (not shown) taking these uncertainties into account can reduce the amplitude of changes in the last half century by about one third. But in all such experiments, significant decreases are still simulated for the transition from the Middle Ages to the Little Ice Age.

[20] The reconstructions of sea level change over the last millennium are also subject to a number of complications. Despite these and other uncertainties, using a model that has been tested against surface proxy temperatures suggests significant changes in ocean heat content and sea level during the last millennium. Greenhouse gas forcing dominates the 20th century rise in ocean heat content. Further experiments with coupled models would be desirable in assessing additional details of such changes.

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