Climate models without preindustrial volcanic forcing underestimate historical ocean thermal expansion

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[1] Episodic explosive volcanic eruptions are a natural part of the climate system but are often omitted from atmosphere-ocean general circulation model (AOGCM) preindustrial spin-up and control experiments. This omission imposes a negative bias on ocean heat uptake in simulations of the historical period. In models of a range of complexity, we find that global-mean sea level rise due to thermal expansion during the last ∼150 years is consequently underestimated by 5–30 mm, which is a substantial proportion of the model mean of 50 mm in Coupled Model Intercomparison Project Phase 3 AOGCMs with anthropogenic forcing only, and is therefore important in accounting for 20th century sea level rise. We test and recommend a procedure for removing the bias.
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1. Introduction

[2] Explosive volcanic eruptions of a range of magnitudes at irregular intervals cause a natural radiative forcing of the climate system, through injection of sulphur dioxide into the stratosphere, producing an aerosol which reflects some incident solar radiation for a few years. Since volcanoes have always occurred, we may assume that the climate has adjusted to the long-term time-mean radiative effect of volcanic stratospheric aerosol. This time mean should therefore be the reference level for measuring volcanic radiative forcing.

[3] For short periods immediately after large eruptions, there is a large negative radiative perturbation, e.g., about –3 W m^{-2} following the Mount Pinatubo eruption of 1991. The climate system loses heat during these episodes, and since the majority of its heat capacity is in the ocean, most

of the heat loss is from the ocean. The remainder of the time, when there is less stratospheric volcanic aerosol than the long-term mean, there is a small positive volcanic radiative forcing (relative to the long-term mean), resulting in an ocean warming tendency. In the time mean of several decades, we expect a negative anomaly in the rate of change of ocean heat content if there is more volcanic activity than is typical of the long term, and a positive anomaly if there is less. On the long term, defined by the timescales of millennia required for adjustment of the deep ocean, the perturbing effect of variable volcanic forcing on ocean heat content will average to zero.

[4] The usual practice in climate modeling has been to run spin-up and control experiments with preindustrial atmospheric composition but without volcanic forcing. Experiments to simulate climate change since the mid- or late 19th century prescribe time-dependent atmospheric composition, especially regarding anthropogenic greenhouse gases and aerosols. These are referred to as "historical" simulations; they cover the period during which global-mean surface air temperature change can be estimated from instrumental records. Historical simulations usually include variations in volcanic aerosol. With respect to the control simulation, which runs in parallel and provides the reference state, the volcanic forcing in the historical simulation is zero when there is no volcanic aerosol. Therefore, the time-mean historical volcanic forcing is negative in the simulated climate system, rather than zero, as it is in the real climate system. From the start of the climate model historical simulation, the negative time-mean volcanic forcing causes a cooling tendency in the ocean [*Gregory*, 2010]. This long-term ocean heat loss is a "spin-up" problem, an artefact of the experimental design.

[5] In the Coupled Model Intercomparison Project Phase 3 (CMIP3), the ensemble mean of atmosphere-ocean general circulation models (AOGCMs) which include volcanic forcing in their historical simulations (the "V" models, green solid line in Figure 1) shows about 40% less ocean heat uptake since 1860 than the ensemble mean of the AOGCMs without volcanic forcing ("non-V" models, black solid line in Figure 1). Both ensembles include the increasingly positive anthropogenic forcing, which gives the ocean a warming tendency. (We show results only up to 2000 because most CMIP3 experiments end at around this year.) In this paper, we test the hypothesis, following *Gregory* [2010], that the smaller heat uptake in the V models is an artefact due to the additional time-mean negative forcing in these models. It is important to establish whether this is the explanation, and if so correct for it, because it implies that the V models underestimate historical ocean heat uptake,

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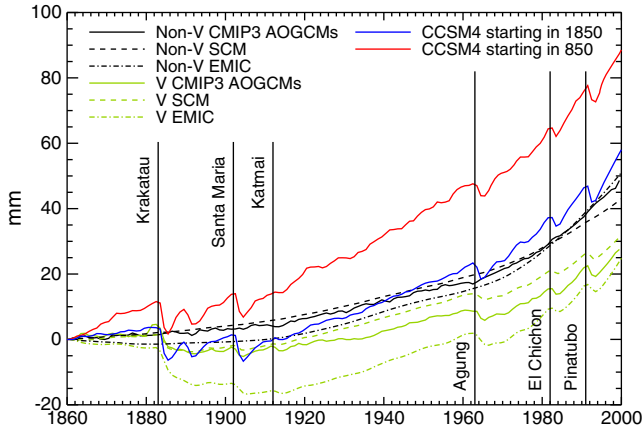
Figure 1. Global-mean sea level rise (mm) due to thermal expansion relative to 1860 simulated by the ensemble mean of CMIP3 AOGCMs, the ensemble mean of CMIP3 emulations by the simple climate model (SCM), and the Earth system model of intermediate complexity (EMIC), with anthropogenic forcing only (non-V) and with both natural and anthropogenic forcing (V), and by the Community Climate System Model 4.0 (CCSM4) AOGCM starting in the years 1850 or 850. Ocean heat uptake simulated by the SCM was converted to sea level rise using the CMIP3 ensemble-mean expansion efficiency of heat of 0.12 m YJ^{-1}, 1 YJ = 10^{24} J (this quantity is described and estimated by [*Kuhlbrodt and Gregory*, 2012]). The vertical lines indicate the years in which major volcanic eruptions occurred.

and hence ocean thermal expansion, which is an important contribution to 20th century sea level rise [*Gregory et al.*, in press].

[6] In addition to the problem due to omitted volcanic forcing, AOGCMs also exhibit the well-known phenomenon of "climate drift," due to the spin-up integration being too short for the model to reach its steady state before the control and historical integrations begin. Following the customary method, we correct for this problem in our AOGCM results by quantifying time-dependent forced climate change as the difference between the results of the

historical and control integrations for corresponding years, relying on the assumption that control climate drift and historical forced climate change combine linearly.

2. Spin-up Including Volcanic Forcing

[7] We expect that the tendency for persistent ocean heat loss will be eliminated if a model is integrated with volcanic forcing for long enough (at least 1000 years) that the ocean has time to adjust to the time-mean effect. We test this using a pair of experiments carried out with the National Center for Atmospheric Research CCSM4 AOGCM [*Gent et al.*, 2011], which was spun up without volcanic forcing. One experiment is 1150 years long, using historical forcings for 850–2000 including volcanic forcing (zero or negative with respect to the spin-up); the other is 150 years, for 1850–2000. During 1850–2000, a sudden drop in ocean heat content (expressed as thermal expansion) can be seen following each large volcanic eruption (Figure 1), as in the CMIP3 V ensemble. However, the experiment beginning in 850 shows a greater rate of ocean warming between the volcanic eruptions, giving 30 mm more thermal expansion during 1860–2000. Note for instance that the ocean is warming before the Krakatau eruption, because the long historical simulation with volcanoes cools the subsurface ocean, giving it a tendency to take up heat from the surface whenever the ocean surface temperature is not depressed by volcanic forcing.

[8] The fractional difference in thermal expansion between the CCSM4 experiments is similar to that between the CMIP3 V and non-V ensemble means, although the absolute thermal expansion in this particular AOGCM is larger than in the ensemble mean. The CCSM4 results thus support the hypothesis that historical ocean thermal expansion is underestimated in simulations which have been spun up without volcanic forcing.

[9] Such long experiments have been done in few AOGCMs because of the computational expense, so we have made use of two computationally less demanding climate models:

[10] The MAGICC simple climate model (SCM) [*Meinshausen et al.*, 2011a], which comprises a one-

Table 1. Naming Convention for Experiments

The experiments are referred to as non-V, Cst0VarN, VarNVarN, CstNVarN, Cst0Var0, and Cst0CstN-only. Non-V has no volcanic forcing at any time. Cst0CstN-only has no forcing other than volcanic; all the other experiments include anthropogenic forcing. Apart from non-V, the experiment names have two parts, interpreted following this table. The first half of the name describes the volcanic forcing in the spin-up which produces the starting state for the historical and control simulations:

Cst0	Constant zero volcanic aerosol, as has been customary in AOGCM spin-up integrations
VarN	Time-varying historical volcanic forcing, negative when volcanic aerosol is present, zero when there is no volcanic aerosol, for 1000–1860 in the SCM, repeated three times in the EMIC, obtained from *Crowley* [2000]
CstN	Constant negative volcanic forcing equal to the time-mean of the historical period

The second half of the name describes the volcanic forcing in the historical simulation:

Var0	Time-varying volcanic forcing anomalized with respect to its time-mean, thus having zero time-mean by construction
VarN	Time-varying volcanic forcing, negative or zero like VarN spin-up
CstN	Same as CstN spin-up

In each half of the name:

Cst	Constant in time
Var	Time-varying
0	Zero time-mean
N	Negative time-mean

dimensional (vertical) hemispherically averaged ocean model coupled to a globally and vertically averaged energy balance model of the atmosphere. MAGICC emulates the CMIP3 AOGCMs individually by using different settings for various parameters, particularly the climate sensitivity, the land-ocean ratio of surface warming and the ocean vertical thermal diffusivity. The calibration takes account of the omission of volcanic forcing in the CMIP3 spin-up and control experiments [*Meinshausen et al.*, 2011b].

[11] The Bern2.5D Earth system model of intermediate complexity (EMIC), which comprises a zonally averaged dynamic ocean model resolving the major ocean basins, coupled to a zonally and vertically averaged energy and moisture balance model of the atmosphere [*Stocker et al.*, 1992; *Knutti et al.*, 2002]. In this study, we use an equilibrium climate sensitivity of 3 K and a vertical ocean diffusivity of 4.5×10^{-5} m^2 s^{-1}.

[12] In these models, all forcing agents are represented by applying their radiative forcings to the atmosphere energy budget; volcanic aerosol is not explicitly simulated. Historical experiments with these models use natural and anthropogenic forcings for 1860–2010 from http://www.pik-potsdam.de/~mmalte/rcps.

[13] Like CMIP3 V models, experiments Cst0VarN and VarNVarN with the SCM and the EMIC have time-varying historical volcanic forcing which is negative when there is volcanic aerosol, and zero when there is none (notation explained in Table 1, experimental design illustrated by Figure 2). Cst0VarN has zero volcanic forcing in its spin-up, like CMIP3 V models and CCSM4 beginning in 1850, while VarNVarN has a long spin-up with time-varying volcanic forcing following the reconstruction of *Crowley* [2000], like CCSM4 beginning in 850. As with CCSM4, thermal expansion in VarNVarN by the end of the historical period is greater than in Cst0VarN and is about the same as in non-V.

[14] In both the SCM and the EMIC, there is almost no difference between the thermal expansion obtained after spin-ups of the same length with time-varying volcanic forcing (VarNVarN) or with constant volcanic forcing (CstNVarN) (Figure 2) [cf. *Gregory*, 2010]. In CstNVarN, the volcanic forcing in the spin-up is the time mean of the historical period, which is similar to that for the last millennium as a whole. (Relative to zero for no volcanic aerosol, the time-mean forcing is –0.18 W m^{-2} for 1000–1998 and –0.22 W m^{-2} for 1860–1998; *Crowley* [2000].)

3. Volcanic Forcing with Zero Time Mean

[15] Starting from a state without volcanic aerosol, it is not generally feasible to carry out an AOGCM spin-up integration of the millennia required to achieve a steady state under VarN forcing. This problem could be avoided by modeling the volcanic forcing as an anomaly with respect to the long-term time-mean radiative effect of volcanoes, as in the real world, so that it has zero time mean by construction and is positive when there is no volcanic aerosol [*Gregory*, 2010].

[16] This method cannot be used in AOGCMs whose input is volcanic aerosol concentration, which cannot be negative, but we have tested it in experiment Cst0Var0 with the SCM and the EMIC, whose input is radiative forcing, which can be of either sign. In this experiment, the model
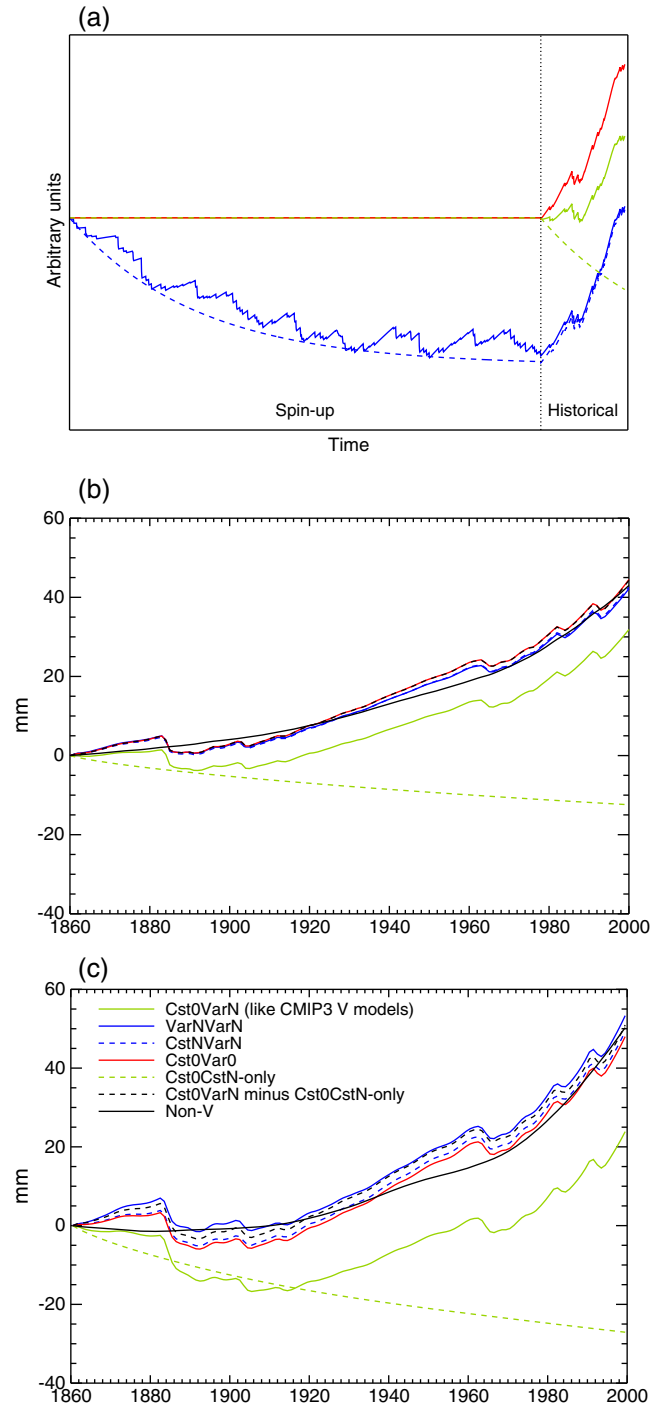

Figure 2. Global-mean sea level rise due to thermal expansion. The key is the same in all panels. (a) Schematic of the spin-up and historical experiments, relative to the start of the spin-up. This plot is in arbitrary units and does not show actual model results. (b, c) Results (mm) for the historical period from the simple climate model (SCM) and the Earth system model of intermediate complexity (EMIC), relative to the 1860 level.

is spun up with zero volcanic forcing, and the historical time-varying volcanic radiative perturbation is anomalized with respect to its time mean. The historical thermal expansion is almost the same in Cst0Var0 as in VarNVarN and CstNVarN (Figure 2).

4. Correction of Bias Due to Omitted Volcanic Forcing

[17] A feasible method for correcting the bias in AOGCM historical integrations due to the omitted volcanic forcing in the spin-up and control is to quantify it with an additional experiment, Cst0CstN-only, beginning from the same control state as the historical experiment, with constant volcanic forcing equal to the time mean in the historical period, and all other forcings as in the control [*Gregory*, 2010], i.e., without historical anthropogenic forcing. Cst0CstN-only is run in parallel to the historical experiment Cst0VarN and is of the same length. With the usual assumption that the responses to forcings combine linearly, the difference between experiments Cst0VarN and Cst0CstN-only gives the corrected estimate of the time-dependent response of the climate system to historical forcing; because by subtracting the response to historical CstN from the response to historical VarN, we estimate the response to historical Var0, which is what we want. Experiment Cst0CstN-only is computationally much less demanding than a multimillennial spin-up experiment including volcanoes, and the method could moreover be used to correct the underestimate of thermal expansion in existing data from CMIP3 and CMIP5 (CMIP Phase 5) models which did not have a long volcanic spin-up. Comprehensive information is not yet available about the treatment of volcanic forcing in CMIP5 models. Some of them include volcanic forcing in their spin-up and control experiments, but not all of them do, and the ensemble mean of available CMIP5 historical experiments with natural forcings only shows a negative trend in thermal expansion.

[18] We have tested the proposed method using the SCM and the EMIC. We find that the difference in thermal expansion between Cst0VarN and Cst0CstN-only is virtually identical with thermal expansion in Cst0Var0 (Figure 2), and hence very similar to non-V, in accordance with the hypothesis.

[19] The ACCESS1.0 and ACCESS1.3 [*Bi et al.*, in press] and Commonwealth Scientific and Industrial Research Organisation (CSIRO)-Mk3.6.0 AOCGMs [*Rotstayn et al.*, 2012] do not have volcanic forcing in their preindustrial spin-up and control integrations, so their CMIP5 historical integrations are Cst0VarN experiments. We therefore expect them to underestimate the historical thermal expansion. By running Cst0CstN-only experiments, we have quantified the underestimate as 5–10 mm in ACCESS1.0 and ACCESS1.3 and about 20 mm in CSIRO-Mk3.6.0 (Figure 3).

[20] The HadCM3 AOGCM [*Gordon et al.*, 2000] was run for over 7000 years with constant volcanic aerosol and other preindustrial forcings, i.e., a CstN spin-up, and eventually reached a steady state. Starting from this state, we have run an experiment with no volcanic aerosol and another with doubled volcanic aerosol. With respect to the CstN spin-up, these experiments have positive and negative forcings, respectively, of equal magnitude, and consequently, they produce responses of opposite signs whose magnitudes are not statistically significantly different (Figure 3). Neither of these experiments is the proposed Cst0CstN-only, but the forcing with respect to the spin-up has the same magnitude as Cst0CstN-only. The effect on thermal expansion is about 15–20 mm over 140 years.
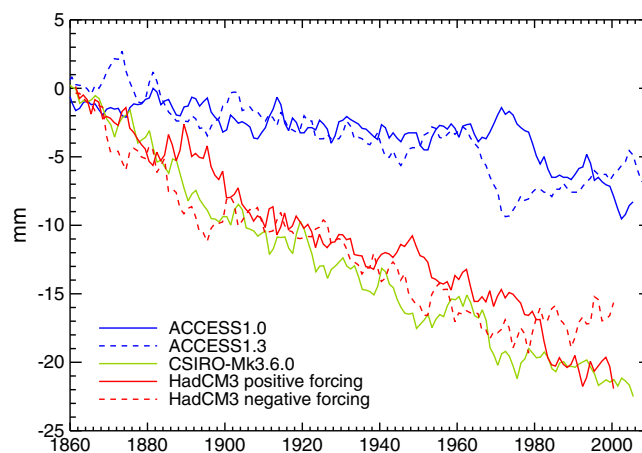

Figure 3. Global-mean sea level rise (mm) due to thermal expansion in AOGCM experiments with constant volcanic forcing of magnitude equal to the time-mean volcanic forcing of the historical period. In Table 1, this is experiment Cst0CstN-only. Thermal expansion as a function of time in the control experiment has been subtracted to remove climate drift which is unrelated to volcanic forcing, and the difference is shown relative to the level at the start of the experiment (1860 for HadCM3, 1850 for the others). In the case of HadCM3 positive forcing, the sign of the thermal expansion has been changed for plotting; in the other cases, both the forcing and the thermal expansion are negative.

5. Conclusions

[21] If an AOGCM control simulation omits volcanic forcing, then including it in simulations of the historical period (since the mid- to late 19th century) imposes a time-mean negative forcing on the climate system and hence a negative bias on simulated ocean heat uptake and global-mean sea level rise due to thermal expansion. From experiments with a simple climate model (SCM), an Earth system model of intermediate complexity (EMIC) and AOGCMs, we find that the underestimate of global-mean sea level rise due to thermal expansion in the last $\sim$150 years lies in the range 5–30 mm, or 0.0–0.2 mm a^{-1}, which is a large proportion of the ensemble mean of 27 mm in the CMIP3 AOGCM historical simulations with natural forcings. The CMIP3 ensemble mean without natural forcings (i.e., with anthropogenic forcing only) gives 50 mm. The difference of 23 mm could plausibly be explained by the negative bias, and correcting it helps to account for observed 20th century global-mean sea level rise [*Gregory et al.*, in press].

[22] As a proportion of the total, the underestimate is smaller for the decades since 1960, during which anthropogenic warming has been larger. *Domingues et al.* [2008] showed that the ensemble mean of CMIP3 V models underestimated thermal expansion in the upper 700 m of the ocean by about 10%, or about 0.05 mm a^{-1}.

[23] The most realistic way to prepare an AOGCM for a historical simulation would be to initialize it thousands of years in the past and run it forward with actual forcings. However, such long simulations are in general prohibitively lengthy for AOGCMs in terms of wallclock and CPU time. We have shown with the EMIC and the SCM that the error can be corrected by subtracting from the historical experiment a parallel experiment with volcanic forcing equal to

the time mean in the historical period. Because the magnitude of the correction is model-dependent, we recommend that this experiment should be carried out for any AOGCM which does not include volcanic forcing at this level in its spin-up and control and should be used instead of the control for subtracting climate drift.

References

Bi, D., et al. (in press), The ACCESS coupled model: Description, control climate and evaluation, *Aust. Met. Oceanog. J.*

Crowley, T. J. (2000), Causes of climate change over the past 1000 years., *Science*, 289, 270–277.

Domingues, C. M., J. A. Church, N. J. White, P. J. Gleckler, S. E. Wijffels, P. M. Barker, and J. R. Dunn (2008), Improved estimates of upper-ocean warming and multi-decadal sea-level rise, *Nature*, 453, 1090, doi:10.1038/nature07080.

Gent, P. R., et al. (2011), The community climate system model version 4, *J. Climate*, 24, 4973–4991, doi:10.1175/2011JCLI4083.1.

Gordon, C., C. Cooper, C. A. Senior, H. Banks, J. M. Gregory, T. C. Johns, J. F. B. Mitchell, and R. A. Wood (2000), The simulation of SST, sea ice extents and ocean heat transports in a version of the Hadley Centre coupled model without flux adjustments, *Clim. Dyn.*, 16, 147–168.

Gregory, J. M. (2010), Long-term effect of volcanic forcing on ocean heat content, *Geophys. Res. Lett.*, 37, L22701, doi:10.1029/2010GL045507.

Gregory, J. M., et al. (in press), Twentieth-century global-mean sea-level rise: Is the whole greater than the sum of the parts? *J. Climate.*

Knutti, R., T. F. Stocker, F. Joos, and G. K. Plattner (2002), Constraints on radiative forcing and future climate change from observations and climate model ensembles, *Nature*, 416, 719–723.

Kuhlbrodt, T., and J. M. Gregory (2012), Ocean heat uptake and its consequences for the magnitude of sea level rise and climate change, *Geophys. Res. Lett.*, 39, L18608, doi:10.1029/2012GL052952.

Meinshausen, M., S. C. B. Raper, and T. M. L. Wigley (2011a), Emulating coupled atmosphere–ocean and carbon cycle models with a simpler model, MAGICC6 Part 1: Model description and calibration, *Atmos. Chem. Phys.*, 11, 1417–1456, doi:10.5194/acp-11-1417-2011.

Meinshausen, M., T. M. L. Wigley, and S. C. B. Raper (2011b), Emulating atmosphere–ocean and carbon cycle models with a simpler model, MAGICC6 Part 2: Applications, *Atmos. Chem. Phys.*, 11, 1457–1471, doi:10.5194/acp-11-1457-2011.

Rotstayn, L. D., S. J. Jeffrey, M. A. Collier, S. M. Dravitzki, A. C. Hirst, J. I. Syktus, and K. K. Wong (2012), Aerosol- and greenhouse gas-induced changes in summer rainfall and circulation in the Australasian region: A study using single-forcing climate simulations, *Atmos. Chem. Phys.*, 12, 6377–6404, doi:10.5194/acp-12-6377-2012.

Stocker, T. F., D. G. Wright, and L. A. Mysak (1992), A zonally averaged, coupled ocean-atmosphere model for paleoclimate studies, *J. Climate*, 5, 773–797.