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Krakatau's long goodbye in the Ocean

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State-of-the-art climate models suggest that 20th Century ocean warming and sea-level rise were substantially reduced by the 1883 eruption of Krakatau. Volcanically induced cooling of the ocean surface penetrated into deeper layers where it persisted for decades. We find that volcanic eruptions have longer lasting effects than previously suspected[1], sufficient to offset a large fraction of ocean warming and sea-level rise caused by anthropogenic influences over the 20th Century.

We examine the latest suite of coupled ocean-atmosphere model experiments that include time-varying external forcings (e.g., changes in greenhouse gases, solar irradiance, sulfate aerosols and volcanic aerosols) for the period 1880-2000 (see Methods). These models have differences in physics, resolution, initial conditions, "spin-up" and ocean-atmosphere coupling procedures, as well as different combinations of external forcings. Uncertainties in both the applied forcings and in the model responses to them are therefore inherent in our investigation.

We compare the 1880-2000 global ocean heat content (HC) evolution in six models that included the effects of volcanic eruptions (V) with six that did not (see Methods). Observations (which are subject to uncertainties arising from incomplete, space- and time- varying coverage[2,3]) suggest that the HC of the upper 3000m of the ocean increase at a rate of 0.33×10^{22} J/yr over 1955-1998. This is in closer agreement with the V simulations (average: 0.2×10^{22} J/yr, 1 s.d.: 0.16×10^{22} J/yr) than the simulations without V (average: 0.78×10^{22} J/yr, 1 s.d.: 0.25×10^{22}J/yr).

An abrupt HC drop in the V simulations (Fig. 1a) follows the 1883 Krakatau eruption, augmented by much smaller eruptions in 1886 and 1888. Volcanic aerosols scatter sunlight and result in a cold ocean surface temperature anomaly. This is gradually subducted into deeper layers[1,4], where it persists for decades (Fig. 1b). While late 20th Century surface warming is apparent in all V simulations, a cold anomaly remains discernible at depth. In spite of substantial differences in model formulations and applied external forcings (and, in particular, uncertainties in pre-satellite era volcanic forcing[5], see Methods), the distinction between the simulations with and without V in Fig.1 is striking. Although solar forcing is only included in the V simulations, its effect is minimal.

An oceanic response to the 1991 Pinatubo eruption, which was comparable to Krakatau in terms of its radiative forcing, has been identified in satellite altimetry data[1]. The simulated HC recovery after Pinatubo appears to occur much more rapidly than for Krakatau (Fig. 1a). This disparity arises because the Pinatubo response is super-imposed on a non-stationary background of large and increasing greenhouse gas forcing. The HC effects of Pinatubo and other late 20th Century eruptions are offset by the observed warming of the upper ocean, which is primarily due to anthropogenic influences[6].

Ocean warming (cooling) contributes to sea-level changes via thermal expansion (contraction). Global-mean thermal expansion (TE) is highly correlated with HC changes, and thus TE comparisons between the V and non V simulations look much like Fig. 1a. TE increases at the end of the 20th Century (relative to 1882, the year before Krakatau) are appreciably less for simulations with V (average: 1.7 cm, 1 s.d.: 1.8 cm) than for the simulations without V (average: 6.3 cm, 1 s.d.: 2.2 cm).

In model simulations, Krakatua has long lasting effects, offsetting a large fraction of ocean heat content changes and thermal expansion caused by 20th Century anthropogenic influences. These results are robust to current uncertainties in climate models and in the historical forcings applied to them. Inclusion of volcanic forcing from Krakatau (and, by implication, from even earlier eruptions) is important for a reliable simulation of historical increases in ocean heat content and sea-level change due to thermal expansion.

600 words

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Figure Legends:

Figure 1: Simulations (1880-2000) with and without volcanic forcing (V). **a**: Global ocean heat content (10^{22} Joules). Shading represents the ± 1 s.d. range of simulations with V (blue) and without V (green) about the corresponding multi-simulation means (white lines). **b**: Global ocean temperature anomalies (degrees C) as a function of depth (meters) for the mean of the simulations with and without V. The inter-simulation s.d. (not shown) decreases with depth, increases with time, and is generally larger for the V simulations. Purple shading shows an estimate of stratospheric aerosol optical depth changes (arbitrary scale) associated with volcanic eruptions (see Methods).

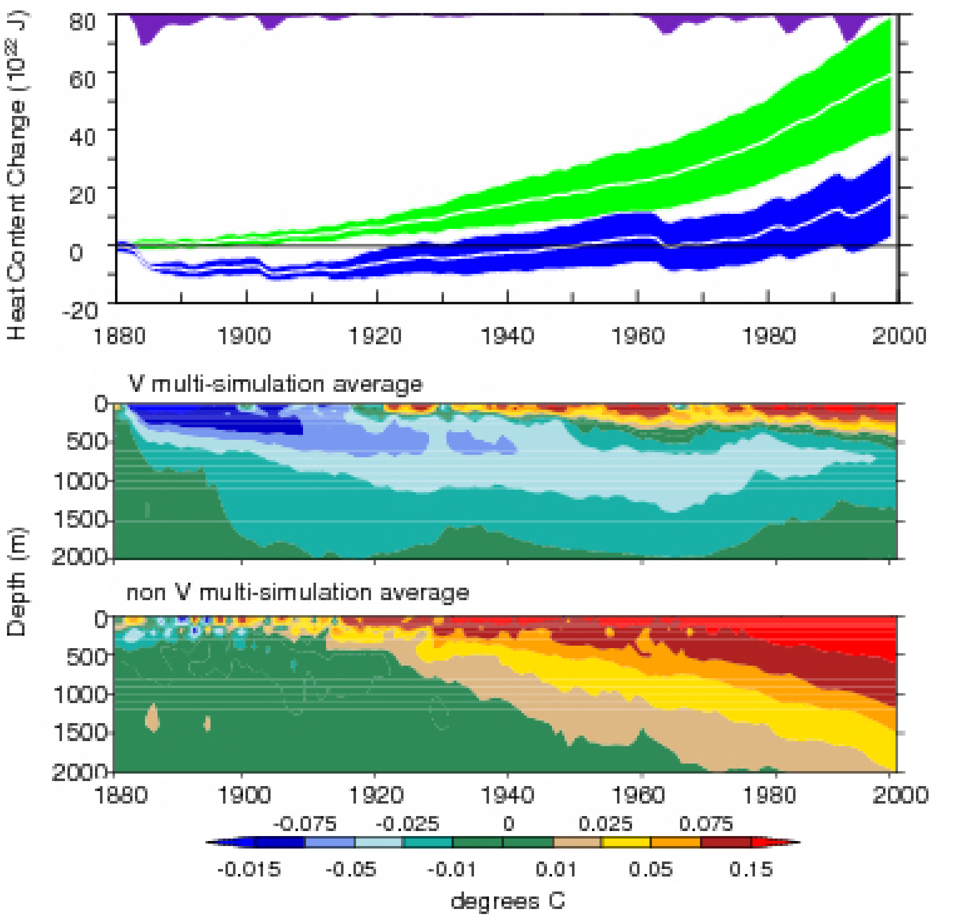
Heat Content Change (10²² J)
80
60
40
20
0
-20
1880
1900
1920
1940
1960
1980
2000
V multi-simulation average
Depth (m)
0
500
1000
1500
2000
non V multi-simulation average
-0.075
-0.025
0
0.025
0.075
-0.015
-0.05
-0.01
0.01
0.05
0.15
degrees C

FIGURE 1

Supplementary Information

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METHODS

Coupled Model Simulations

Climate modeling experiments now routinely employ a range of time-varying external forcings, including increases in greenhouse gases and sulfate aerosols and changes in solar variability and volcanic aerosol loadings. Virtually all major climate modeling groups recently performed coupled atmosphere-ocean General Circulation Model (A-OGCM) simulations of 20th Century climate. These experiments were proposed by the Working Group on Coupled Modeling (WGCM) of the World Climate Research Programme, and were performed in support of the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). The IPCC simulations were archived by the Program for Climate Model Diagnosis and Intercomparison (PCMDI), and have been made available to the climate research community.

The subset of models examined here represents those for which all ocean data required for calculating heat content and expansion changes were available at the time of the study. To date several groups have submitted more than one realization to the database; we use only the first realization. Table S1 summarizes the models used as well as the external forcings employed. Model characteristics and experimental configuration are summarized for each simulation at:

http://www-pcmdi.llnl.gov/ipcc/model_documentation/ipcc_model_documentation.php

Table S1. Forcings used in IPCC simulations of 20th century climate change. This Table was compiled using information provided by the participating modeling centers (see http://www-pcmdi.llnl.gov/ipcc/model.documentation). Eleven different forcings are listed: well-mixed greenhouse gases (G), tropospheric and stratospheric ozone (O), sulfate aerosol direct (SD) and indirect effects (SI), black carbon (BC) and organic carbon aerosols (OC), mineral dust (MD), sea salt (SS), land use/land cover (LU), solar irradiance (SO), and volcanic aerosols (V). "Y" denotes inclusion of a specific forcing. As used here, "inclusion" means specification of a time-varying forcing, with changes on inter-annual and longer timescales.

		MODEL	G	O	SD	SI	BC	OC	MD	SS	LU	SO	V
VOLCANIC FORCING	1	NCAR-CCSM3	Y	Y	Y		Y	Y				Y	Y[1]
	2	GISS-EH	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y[2]
	3	GISS-ER	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y[2]
	4	GFDL-CM2.0	Y	Y	Y		Y	Y			Y	Y	Y[3]
	5	MIROC3.2(medres)	Y	Y	Y		Y	Y	Y	Y	Y	Y	Y[4]
	6	UKMO-HadCM3-V	Y	Y	Y	Y							Y[5]
NO VOLCANIC FORCING	1	CCCma-CGCM3.1(T47)	Y		Y								
	2	CNRM-CM3	Y	Y	Y		Y						
	3	CSIRO-Mk3.0	Y		Y								
	4	FGOALS-g1.0	Y		Y								
	5	GISS-AOM	Y		Y					Y			
	6	UKMO-HadCM3	Y	Y	Y	Y							

[1] Uses S1 volcanic forcing.
[2] Uses updated version of S2 volcanic forcing (for details see S3).
[3] Uses "blend" between S2 and S4.
[4] Volcanic forcing "changed according to historical data". Further details currently unavailable.
[5] Details of volcanic forcing in S5

Calculation Description: While none of the models used here employs flux adjustments, most still show appreciable control-run drift in ocean temperatures, particularly in the intermediate and deep ocean. To account for this, the signals in ocean heat content were defined by subtracting temporally-coincident control results from the perturbed-run data. The global ocean volume-integrated heat content is calculated from the annual mean temperature of each grid cell. For the thermal expansion calculations we use the standard equation of state for seawater with values of the coefficient of thermal expansion taken from UNESCO, *International Oceanographic Tables*, vol. 4, Paris, 1987. As with heat content, the expansion is calculated at each grid cell. Sea level changes are determined by dividing the total volume changes by the global ocean surface area. Climatological salinity was used in calculating thermo-steric expansion. These methods and approximations have been demonstrated to be appropriate for global average calculations and applied by previous investigators[S6,S7].

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