Stratospheric Aerosol Cooling Impacts Accumulated in Oceans

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Sulfate aerosols resulting from strong volcanic explosions last in the lower stratosphere for 2-3 years. Therefore it was traditionally believed that volcanic impacts could produce only short-term transient climate perturbations. However, the ocean integrates volcanic radiative cooling developing disturbances on a spectrum of longer time scales. This study focuses on quantification of long-term ocean-related processes forced in the climate system by explosive volcanism. We employ the coupled climate model CM2.1, developed recently at the NOAA's Geophysical Fluid Dynamics Laboratory (GFDL), to simulate the 1991 Pinatubo and the 1815 Tambora eruptions, which were the largest in the 20th and 19th centuries, respectively. We conduct a few series of ensemble runs accounting for the observed phase of *El Niño-Southern Oscillation (ENSO)* for each volcano. The simulated anomalies of sea level, surface air temperature, and ocean heat content compare well with available observations for the Pinatubo period. The stronger Tambora forcing produces responses with higher signal-to-noise ratio. Volcanic impact tends to strengthen the meridional overturning circulation. The sea ices appear to be sensitive to volcanic forcing especially during the warm season. The volcanic temperature signals scale roughly linear with respect to radiative forcing. Volcanic impacts on the ocean provide an independent means of assessing climate sensitivity. Because of the extremely long relaxation time of ocean subsurface temperature, sea level, and overturning circulation, their perturbations caused by the Tambora eruption could well last into the beginning of the 20th century.

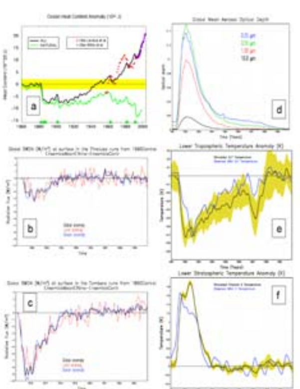

Figure 1

Figure 1. a) The ensemble mean ocean heat content anomalies in the 0-3000 m ocean layer with "ALL" and "NATURAL" forcings. b) The solar downward flux anomaly (W/m2) averaged globally, over land, and over ocean for the Pinatubo ensemble and c) for the Tambora ensemble. d) The total optical depth of stratospheric aerosols for the Pinatubo period for different wave length as a function of time. e) The observed and simulated MSU temperature anomalies (K) caused by the Pinatubo eruption for Lower Troposphere, and f) for Lower Stratosphere; yellow shading shows ±2σ ensemble mean variability.

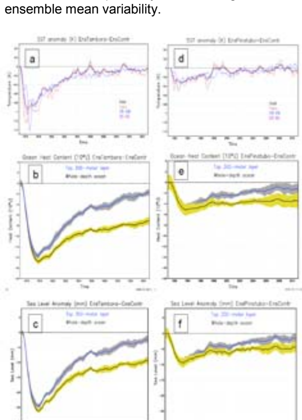

Figure 2

Figure 2. a) The sea surface temperature (SST) anomaly (K) for the Tambora ensemble. b) The ocean heat content (10^{22} J) and c) thermosteric height anomalies (mm) for 300-m and whole depth

Hemispherically Asymmetric Ocean Response

Because the Pinatubo and Tambora radiative impacts are relatively symmetrical in the both hemispheres initially the annual mean temperature anomaly is fairly hemispherically symmetric. However, in 20 years the world's ocean response in the southern and northern hemispheres becomes asymmetric. The cooling signal penetrates to the bottom 5000 m in the high southern latitudes but in the high northern latitudes a warming signal is seen in the deep ocean.

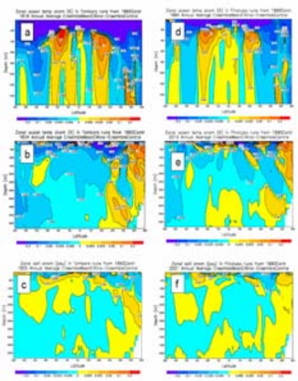

Figure 3

Figure 3. a) The zonal and annual mean ocean temperature anomaly (K) calculated in the Tambora ensemble for year 1818 and b) for year 1834. c) The zonal and annual mean salinity anomaly (psu) in the Tambora ensemble for year 1825. d) is same as a), e) is same as b), and f) is same as c) but in the Pinatubo ensemble for years 1994, 2010, and 2001, respectively.

Strengthening of Meridional Overturning Circulation

The meridional overturning circulation increases in response to the volcanic forcing. The maximum increase is 2.7 Sverdrups (Sv; 1 Sv = 10^6 m^3 s^{-1}) for the Tambora case, and 1.5 Sv for the Pinatubo case. The MOC has inherent decadal time scales of adjustment, and is thus maximum some 5-15 years after the volcanic eruptions. The MOC response to the amplitude of the volcanic forcing is more nonlinear than the temperature response. A volcanically induced cooling leads to reduced precipitation and river runoff at high latitudes of the Northern Hemisphere, thereby leading to more saline (and hence denser) upper ocean conditions in the higher latitudes of the Northern Hemisphere. These conditions destabilize the water column, making them more prone to ocean convection. In addition, the cooling of the upper ocean also increases the upper ocean density, with a similar destabilizing impact. The increased ocean convection tends to enhance the MOC. Further, an enhanced positive phase of the Arctic Oscillation also leads to an MOC increase [*Delworth and Dixon*, 2000]. An increase in MOC also could cause in part the asymmetry of the ocean temperature response in the high northern and southern latitudes.

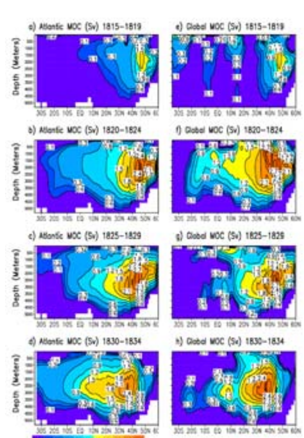

Figure 4

Figure 4. a-d) The five year means MOC anomalies (Sv) from the Tambora ensemble averaged zonally

Poleward Shift of Tropospheric Jets Because of Equatorial Lower Stratospheric Heating Caused by Aerosol Absorption of IR and Solar Radiation

The wind stress increases at 30°S and 30°N, decreases at 50°S and 50°N where the cores of the southern and northern tropospheric jets locate, and increases poleward from those regions at 70°S and 70°N manifesting a slight poleward shift of the jets. A decrease of the wind stress near equator in the southern hemisphere could contribute into the weakening of the equatorial upwelling. However, these effects are fairly weak in the model (two-three percent).

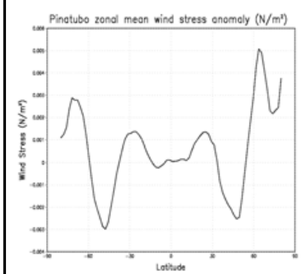

Figure 6. The zonal mean ocean surface wind stress anomaly (N/m^2) averaged for 1991-1995 for the Pinatubo ensemble.

Impact on Sea Ice Extent and Ice Mass

The Maximum Sea Ice Extent anomalies reach 0.8x10^6 km^2 in the Tambora run and 0.6x10^6 km^2 in the Pinatubo run. It takes at least 5 years to develop. So sea ice extent responds more strongly not to the radiative forcing but to ocean temperature and circulation. Accordingly, in the Pinatubo case the sea ice extent relaxes to zero for a decade, and in the Tambora run it remains at 0.6x10^6 km^2 level till the end of the run because ocean cooling remains significant.

The maximum and minimum ice mass scale almost linearly with respect to the radiative forcing. The maximum (minimum) ice mass anomaly reaches 2.9(2.0)x10^{15} kg and 1.0 (0.6)x10^{15} kg in the Tambora and Pinatubo runs, respectively.

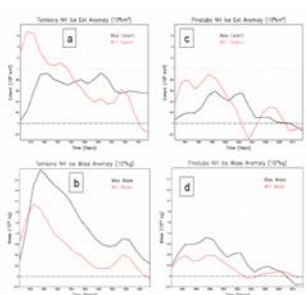

Figure 7

Figure 7. a) The Northern Hemisphere anomalies of maximum and minimum Ice Extent (10^6 km^2) and b) Ice Mass (10^{15} kg) for the Tambora ensemble. c) is same as a) and d) is same as b) but for the Pinatubo ensemble.

Comparison of Observed and Simulated Anomalies of Sea Ice Extent Caused by the Pinatubo Eruption of 1991

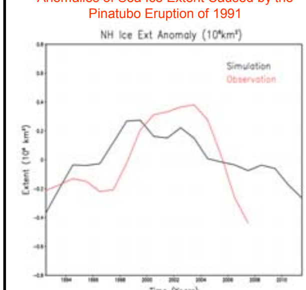

Figure 8

Figure 8. The Northern Hemisphere ice extent anomaly (10^6 km^2) from observations (J. Walsh and W. Chapman data set;

Conclusions

Volcanic eruptions produce long-term impacts on the ocean's subsurface temperature and steric height that accumulate at the current frequency of explosive volcanic events. The accumulated averaged volcanic ocean heat content anomaly reaches about -5.-10.x10^{22} J. The vertical distribution of the temperature change signal is asymmetric at high latitudes. A cooling signal penetrates to depth at high Southern latitudes, while a warming signal penetrates to depth at high latitudes of the Northern Hemisphere. This asymmetry in part forced by an increase in MOC.

Radiative forcing produced by explosive volcanic events that have occurred in the historic period lasts for about 3 years. The volcanically-induced surface temperature anomalies reduce below noise for approximately 7 years. The sea ice responds on the decadal time scale. Deep ocean temperature, sea level, salinity, and MOC have relaxation time of several decades to a century. This suggests that the Tambora subsurface temperature and sea level perturbations could last well into the 20th century (exceeding 1/3 of the Pinatubo maximum impact if e-folding time is about 40 years as we calculated) interfering with the effects of the devastating Krakatau, Santa Maria and Katmai eruptions occurred respectively in 1883, 1902, and 1912 and producing a cumulative impact on the deep ocean thermal structure in 20th century.

Quasi-periodic nature of volcanic cooling facilitates ocean vertical mixing and might have an important effect on the thermal structure of the deep ocean. Therefore it has to be realistically implemented in climate models for calculating "qusi-equilibrium" initial conditions, climate reconstructions, and for future climate projections.

The decrease of ocean steric height in our simulations, caused by the Pinatubo eruption, reaches 9 mm in comparison with 5 mm estimated by *Church et al.* [2005]. In our Tambora simulations the sea level decreases by 25 mm that compares well with [*Gregory et al.*, 2006]. The ocean heat content decreases in the Tambora and Pinatubo runs by 15.x10^{22}J and 5.x10^{22}J, respectively.

Atmospheric temperature anomalies forced by the Pinatubo eruption in the troposphere and lower stratosphere are well reproduced by the model but observed sea level and ocean heat content anomalies are overestimated. This discrepancy is seen in all other model simulations and might be caused by an unaccounted internal ocean variability and/or unknown forcing.

The maximum sea ice extent and ice mass increase in the Tambora (Pinatubo) runs by 0.9x10^6 km^2 (0.5x10^6 km^2) and 2.9x10^{15} kg (1.0x10^{15} kg), respectively. This corresponds to 5% (3%) and 15% (5%) of the model "control" maximum extent and mass in the Tambora (Pinatubo) run. The simulated minimum ice extent is more sensitive to volcanic forcing than the maximum ice extent.

The Atlantic MOC strengthens in the Tambora and Pinatubo runs by 2.7 and 1.8 Sv that corresponds to 13.5% and 9%, respectively.

The ocean heat content, steric height and sea ice mass perturbations scale linearly with respect to volcanic forcing. The MOC and sea ice extent anomalies scale less than linearly.

Acknowledgements

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