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Effects of Mount Pinatubo volcanic eruption on the hydrological cycle as an analog of geoengineering

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[1] The problem of global warming arises from the buildup of greenhouse gases such as carbon dioxide from burning of fossil fuels and other human activities that change the composition of the atmosphere and alter outgoing longwave radiation (OLR). One geoengineering solution being proposed is to reduce the incoming sunshine by emulating a volcanic eruption. In between the incoming solar radiation and the OLR is the entire weather and climate system and the hydrological cycle. The precipitation and streamflow records from 1950 to 2004 are examined for the effects of volcanic eruptions from El Chichón in March 1982 and Pinatubo in June 1991, taking into account changes from El Niño-Southern Oscillation. Following the eruption of Mount Pinatubo in June 1991 there was a substantial decrease in precipitation over land and a record decrease in runoff and river discharge into the ocean from October 1991–September 1992. The results suggest that major adverse effects, including drought, could arise from geoengineering solutions. **Citation:** Trenberth, K. E., and A. Dai (2007), Effects of Mount Pinatubo volcanic eruption on the hydrological cycle as an analog of geoengineering, *Geophys. Res. Lett.*, *34*, L15702, doi:10.1029/2007GL030524.

1. Introduction

[2] The main purpose of this paper is to document the apparent effects of the Mount Pinatubo eruption in June 1991 [*Hansen et al.*, 1992; *Minnis et al.*, 1993] on the hydrological cycle, which showed a remarkable slowing in 1992 as measured by precipitation over land and associated runoff and river discharge into the ocean. If these changes were indeed associated with the stratospheric veil of aerosol that resulted from the eruption, then it has direct implications for the suggestions of geoengineering solutions to global warming [*Crutzen*, 2006]. The central concern with geoengineering fixes to global warming is that the cure could be worse than the disease.

[3] A cooling signature in broad terms is thought to be characteristic of the effects of volcanic eruptions on climate [*Hansen et al.*, 1992; *Minnis et al.*, 1993; *Robock*, 2000; *Jones et al.*, 2003], or at least those that eject significant amounts of material into the stratosphere. Direct injection of particles can have a short-term cooling effect but such particles may not stay very long as they fall out. Rather, the injection of gases such as sulfur dioxide into the stratosphere which are subsequently oxidized to form tiny sulfate particles are the main source of an increase in albedo and net loss of energy [*Robock*, 2000]. Particles in the troposphere are rained out on a time scale of several days, but may remain in the stratosphere for many months. The net radiative effects of volcanic aerosols on surface and tropospheric temperatures [*Wigley*, 2000; *Jones et al.*, 2003; *Free and Angell*, 2002] have the biggest and clearest signal in land temperatures in the second and third summer following tropical eruptions [*Jones et al.*, 2003]. Precipitation and hydrological effects are more difficult to analyze and model [*Broccoli et al.*, 2003].

[4] In the period of available reliable hydrological data, after 1950, there were three large tropical volcanic eruptions (Agung in May 1963, El Chichón in April 1982 and Pinatubo in June 1991). All 3 occurred at or near times of El Niño events, complicating the task of sorting out the volcanic from ENSO signals [*Wigley*, 2000]. The best documented and biggest veil of aerosol by far was from Pinatubo, thus providing the main focus of this article. As Agung is at 8.3°S, its influence over northern land may have been limited or delayed compared with El Chichón (17°N) and Pinatubo (15°N), and global precipitation analyses [*Adler et al.*, 2003] are not available prior to 1979, limiting analysis of the effects before then.

[5] Several studies have documented the effects of the Mount Pinatubo volcanic eruption and resulting stratospheric aerosols that had a peak global visible optical depth of about 0.15 [*Hansen et al.*, 1992; *Minnis et al.*, 1993] on the subsequent climate [*Hansen et al.*, 2002; *Wielicki et al.*, 2005; *Harries and Futyan*, 2006]. Top-of-atmosphere (TOA) radiation measurements such as from the Earth Radiation Budget Satellite (ERBS) show how the veil of debris that formed in or was injected into the stratosphere blocked out the sun and resulted in a significant decrease in absorbed solar radiation (ASR) in the Earth-atmosphere system. This was caused by an increase in albedo by up to 0.007 because of the reflection of up to an additional 2.5 W m^{-2} of solar radiation over the following two years [*Wielicki et al.*, 2005; *Harries and Futyan*, 2006]. Moreover, the drop in radiative forcing is reasonably simulated by models [*Hansen et al.*, 1992, 2002; *Robock*, 2000; *Ammann et al.*, 2003; *Stenchikov et al.*, 2006]. The effect was largest in the Tropics (see Figures 1 and 2).

[6] In the Pinatubo case, the effect was to lower air temperatures, reduce total water vapor in the atmosphere [*Trenberth and Smith*, 2005; *Soden et al.*, 2005], and reduce the outgoing longwave radiation (OLR) back to space with a lag of a few months [*Harries and Futyan*, 2006]. The latter compensates somewhat for the lower ASR but there is nonetheless a loss in net global radiation at TOA signaling a cooling following the eruption (see Figure 2). Several models have simulated decreases in surface temperature [*Hansen et al.*, 1992, 2002; *Robock*, 2000; *Broccoli et al.*,

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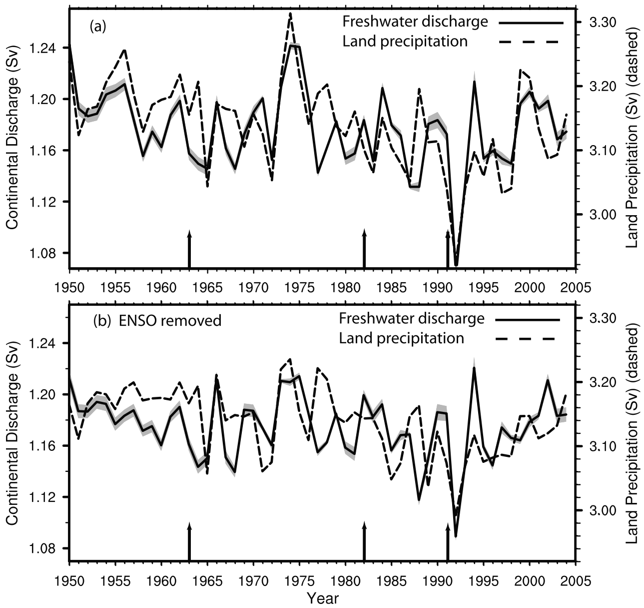

Figure 1. (a) Annual water year (Oct. to Sep.) continental freshwater discharge (solid line, shading indicates ±one standard error, 1 Sv = 10^6 m^3 s^{-1}) into the global oceans from 1950–2004 estimated using historical streamflow records from the world's largest 925 rivers supplemented with simulated streamflow [*Qian et al.*, 2006] using a land surface model forced with observed precipitation and other atmospheric forcing. Also shown is observed precipitation [*Qian et al.*, 2006] (dashed line) integrated over global land areas (1.2 × 10^8 km^3 which excludes some inland drainage areas). The correlation (r) between the two curves is 0.65. (b) As for Figure 1a but with ENSO-related variations removed. The r is 0.42. The year tick marks indicate the mid-point of the Oct.–Sep. period so that the anomaly for 1992 is the mean for Oct. 1991–Sep. 1992. The arrows indicate times of Agung, El Chichón, and Pinatubo eruptions.

2003; *Ammann et al.*, 2003; *Gillett et al.*, 2004] although often with too large an amplitude.

[7] Based on the temperature decreases, it has been proposed that a possible partial solution to global warming may be to emulate the effects of a volcanic eruption by injecting material into the stratosphere as a form of "geo-engineering" [*Crutzen*, 2006; *Wigley*, 2006]. However, global warming is not caused by increased sunshine, rather it arises from the increased greenhouse effect owing to the buildup of greenhouse gases such as carbon dioxide from burning of fossil fuels and other human activities by trapping OLR and thus warming the planet. The effect is about 1% of the natural energy flow [*Karl and Trenberth*, 2003]. In other words, the problem is the increased trapping of OLR by greenhouse gases and the solution proposed is to change the incoming solar radiation.

[8] The primary driver of the climate system is the uneven distribution of incoming and outgoing radiation on Earth. The incoming absorbed solar radiant energy is transformed into various forms (internal heat, potential energy, latent energy, and kinetic energy), moved around in various ways primarily by the atmosphere and oceans, stored and sequestered in the ocean, land, and ice components of the climate system, and ultimately radiated back to space as infrared radiation [*Trenberth and Stepaniak*, 2004]. The requirement for an equilibrium climate mandates a balance between the incoming and outgoing radiation and further mandates that the flows of energy are systematic. These drive the weather systems in the atmosphere, currents in the ocean, and fundamentally determine the climate [*Trenberth and Stepaniak*, 2004]. Reducing incoming solar radiation affects the natural flow of energy through the climate system and the whole operation of the climate system and, in particular, the hydrological cycle.

2. Hydrological Cycle and Volcanoes

[9] We examine the changes in land precipitation and continental freshwater discharge to illustrate the potential hydrological impacts of similar volcanic or geoengineering events. A review of precipitation *P* datasets suitable for our

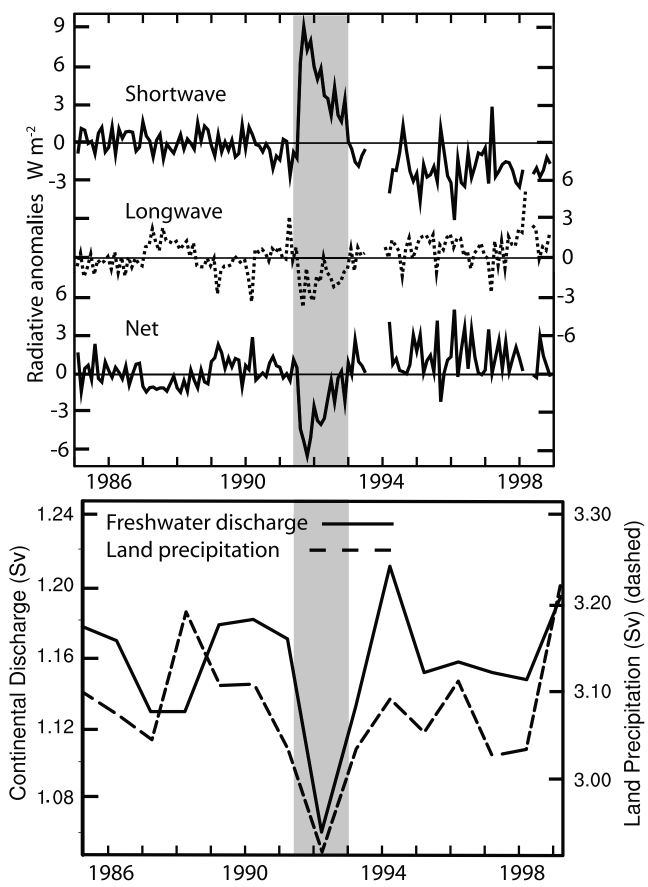

Figure 2. (top) Adapted time series of 20°N to 20°S ERBS non-scanner wide-field-of-view broadband shortwave, longwave, and net radiation anomalies from 1985 to 1999 [*Wielicki et al.*, 2002a, 2002b] where the anomalies are defined with respect to the 1985 to 1989 period with Edition 3_Rev 1 data [*Wong et al.*, 2006]. (bottom) Time series of the annual water year (Oct. to Sep.); note slight offset of points plotted vs. tick marks indicating January continental freshwater discharge and land precipitation (from Figure 1) for the 1985 to 1999 period. The period clearly influenced by the Mount Pinatubo eruption is indicated by grey shading.

purpose [*Trenberth et al.*, 2007] reveals considerable uncertainties over the ocean [*Yin et al.*, 2004] and even over land [*Adam et al.*, 2006] where rain-gauge records are unavailable for many areas and measurement errors occur. As these are mostly systematic, they may not influence anomalies. For reasons discussed by *Qian et al.* [2006], we use a merged land precipitation product which was derived by combining the precipitation for 1948–1996 from *Chen et al.* [2002] with the version 2 of the Global Precipitation Climatology Project (GPCP) data [*Adler et al.*, 2003] for 1997–2004. As all the land precipitation products examined by *Trenberth et al.* [2007] show similar anomalies near 1964 and 1983 and a sharp decline around 1992, our conclusions are not affected by the choice of precipitation products used here. Long-term changes in global mean precipitation (based on GPCP 1979 to 2005) are small [*Curtis and Adler*, 2003; *Gu et al.*, 2007] but there is a strong inverse relationship between land and ocean precipitation in both the annual cycle and the interannual variability [*Gu et al.*, 2007]. During El Niño events there tends to be a decrease in precipitation over land but an increase over the oceans [*Curtis and Adler*, 2003], and during 1983 and 1992 there were El Niños underway.

[10] We use updated streamflow gauge records from 925 of the world's major rivers [*Dai and Trenberth*, 2002] and fill the gaps in this streamflow data set with simulated-streamflow from a stand-alone integration of the Community Land Model (CLM) [*Dickinson et al.*, 2006] driven by observation-based atmospheric forcing [*Qian et al.*, 2006]. The CLM is a comprehensive land surface model that represents the land surface with five primary subgrid land cover types, 16 plant functional types, and 10 layers for soil temperature and water, with explicit treatment of liquid soil water and ice. The CLM-simulated streamflow is highly correlated with streamflow gauge records [*Qian et al.*, 2006], and it is used (through regression) to fill the missing-data gaps in streamflow records from world's major rivers from 1948–2004. This new streamflow data set is then used to construct the continental discharge into the oceans accounting for contributions from the unmonitored areas outside of the 925 river basins [*Dai and Trenberth*, 2002]. The regression error and the difference between the observed and estimated (using the regression and CLM-simulated flow) streamflow are used as a measure of uncertainties for the derived continental discharge.

[11] The time series for the global land precipitation and river discharge into the oceans (Figure 1a) from 1950 through 2004 show the level of natural variability and also the singular nature of the anomalous values in the water year of 1992 (October 1991 to September 1992) following Pinatubo. During the 1992 water year, the precipitation is 3.12 standard deviations (0.069 Sv, computed with 1992 included) below normal and the river discharge is 3.67 standard deviations (0.031 Sv) below normal, both highly statistically significant at <1% level (and <0.1% level for the latter). The 1992 anomalies are much larger than variations for all other years during this 55 year period, including during the much stronger 1982/1983 and 1997/1998 El Niño events. More modest decreases are also seen in 1983 after El Chichón, although these are not statistically significant. However, they were more pronounced over the tropics and the change was significant there [*Gu et al.*, 2007]. There is no clear signal following Agung in 1963 unless it was delayed until 1965.

[12] Owing to the tendency for land precipitation to be reduced during El Niño events, we used linear regression with the Niño 3.4 sea surface temperature index (Figure 1b) to remove the expected effects of El Niño Southern Oscillation (ENSO) on the two series, by performing a regression based on all years but with 1983 and 1992 removed. For precipitation the variance is reduced by 43.9% and for discharge by 35.7%, and the relation between the two series is not as strong, but in both cases the 1992 anomalies are still statistically significant at <1% level.

[13] The TOA tropical broadband radiation anomalies from ERBS [*Wong et al.*, 2006] (Figure 2) illustrate the changes in shortwave reflected (the inverse of ASR), longwave (OLR) and net radiation associated with the Pinatubo eruption and highlight the much larger change in the Tropics than for the global values [*Harries and Futyan*, 2006], with over 6 W m^{-2} decrease in net radiation. For the same period, the precipitation and river discharge values from Figure 1a are also given. Note that the precipitation and discharge anomalies for 1992 are for the period Oct. 1991–Sep 1992, which is before the canonical maximum El Niño warming in late-1992.

[14] The corresponding regional changes in precipitation, runoff streamflow and river discharge are also correspondingly greater in the Tropics (Figures 3a and 3b), a point emphasized by plotting in units of mm/day, while higher latitude effects are better illustrated by the Palmer Drought Severity Index (Figure 3c); a normalized drought index reflecting the balance between atmospheric moisture supply (i.e., precipitation) and demand based on a crude estimate of evapotranspiration (a function of temperature) [*Dai et al.*, 2004]. Widespread regions of moderate or severe drought occurred following the Pinatubo eruption, and the year 1992 has a peak percentage of global land areas under drought conditions [*Dai et al.*, 2004]. Although some of the regional precipitation anomalies shown in Figure 3a (over the maritime continent, the U.S., South America, and Southern Africa) resemble canonical patterns of El Niño-induced precipitation changes, many of the changes (over Europe, South Asia and northern South America) are not El Niño-like or are stronger than ENSO-induced anomalies. The runoff changes (Figure 3b), which directly result in the continental discharge anomaly, largely follow the precipitation anomaly patterns.

[15] We have examined global GPCP precipitation 12-month running means which indicate lowest values in late 1991 to early 1992 of 0.07 mm day^{-1} below the 1979 to 2004 average. Because global ocean values were also slightly below average, it is evident that the large land precipitation decrease in 1992 was not merely a shift in location between land and ocean. This is evidently a characteristic signature that enables the volcanic signal to be distinguished from ENSO effects and it is seen following both the El Chichón and Pinatubo events [*Gu et al.*, 2007]. Only for Pinatubo was a large downward excursion of land precipitation found in model ensemble runs [*Broccoli et al.*, 2003] although a volcanic drying signal is detectable in several models [*Broccoli et al.*, 2003; *Gillett et al.*, 2004].

[16] The coincidence of Pinatubo effects with the natural tendency during the 1992 El Niño event for precipitation to

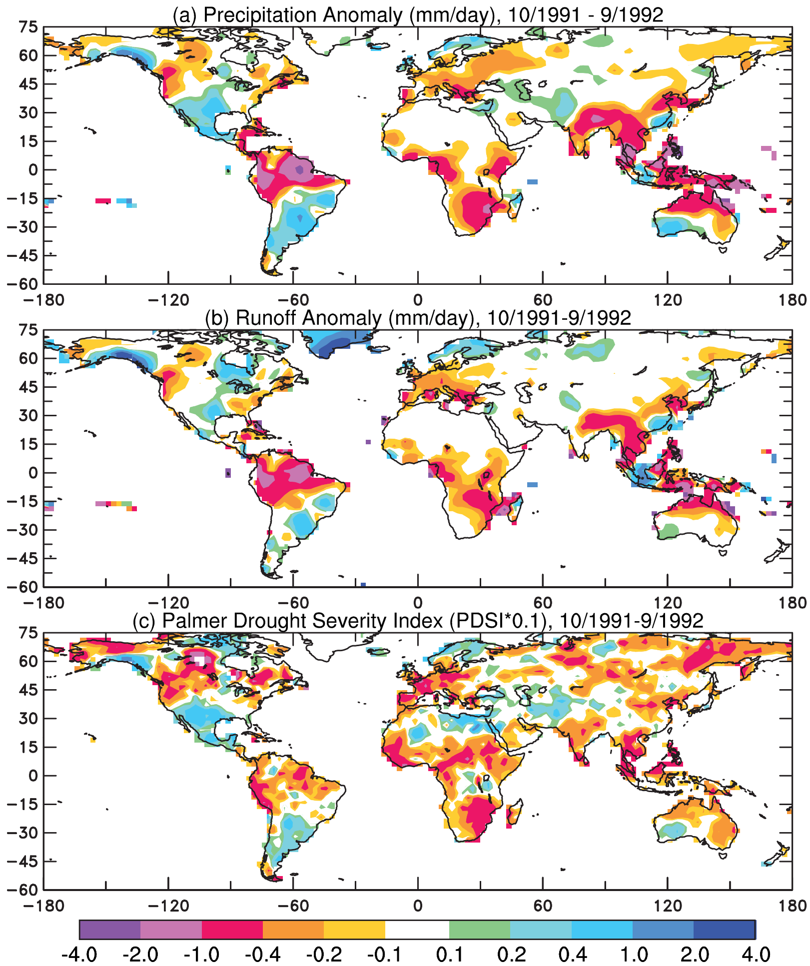

Figure 3. (a) Observed precipitation anomalies (relative to 1950–2004 mean) in mm/day during October 1991–September 1992 over land. Warm colors indicate below normal precipitation. (b) As for Figure 3a but for the simulated runoff [*Qian et al.*, 2006] using a comprehensive land surface model forced with observed precipitation and other atmospheric forcing in mm/day. (c) Palmer Drought Severity Index (PDSI, multiplied by 0.1) for October 1991–September 1992 [*Dai et al.*, 2004]. Warm colors indicate drying. Values less than −2 (0.2 on scale) indicate moderate drought, and those less than −3 indicate severe drought.

move off shore may have exacerbated the effects on the land hydrological cycle. Nonetheless the fact that the 1992 precipitation and discharge anomalies are so much larger than for any other years suggests that the Pinatubo eruption played an important role in the record decline in land precipitation and discharge, and the associated drought conditions in 1992.

3. Implications for Geoengineering

[17] Geoengineering by blocking the sun addresses neither the central problem of climate change nor acidification of the oceans. Instead, adverse effects on the hydrological cycle may result from blocking sunlight before it reaches the Earth surface. More energy absorbed at the surface returns to the atmosphere through evaporation than through radiation or sensible heating [*Kiehl and Trenberth*, 1997], and the latent heat released occurs elsewhere as water vapor is transported many hundreds of kilometers before it condenses in the form of rain or snow. Hence cutting down solar radiation is apt to reduce precipitation and change atmospheric heating patterns that are dominated by latent heat release [*Trenberth and Stepaniak*, 2004]. It would alter a vital link (latent heating) in the flow of energy through the climate system between the incoming and outgoing radiation. This important effect is not included in simple models [*Wigley*, 2006] that involve only surface temperature and respond with surface cooling to a veil of aerosol that cuts out some sunshine.

[18] Creating a risk of widespread drought and reduced freshwater resources for the world to cut down on global warming does not seem like an appropriate fix. Our results suggest that considerable caution should be used regarding any *intentional* human intervention in the climate system that we do not fully understand.

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