Response of Summer Precipitation over Eastern China to Large Volcanic Eruptions

YOUBING PENG

Key Laboratory of Western China's Environmental Systems (Ministry of Education), Lanzhou University, Lanzhou, and Laboratory for Climate Studies, China Meteorological Administration, Beijing, China

CAIMING SHEN AND WEI-CHYUNG WANG

Atmospheric Sciences Research Center, University at Albany, State University of New York, Albany, New York

YING XU

Laboratory for Climate Studies, China Meteorological Administration, Beijing, China

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ABSTRACT

Studies of the effects of large volcanic eruptions on regional climate so far have focused mostly on temperature responses. Previous studies using proxy data suggested that coherent droughts over eastern China are associated with explosive low-latitude volcanic eruptions. Here, the authors present an investigation of the responses of summer precipitation over eastern China to large volcanic eruptions through analyzing a 1000-yr global climate model simulation driven by natural and anthropogenic forcing. Superposed epoch analyses of 18 cases of large volcanic eruption indicate that summer precipitation over eastern China significantly decreases in the eruption year and the year after. Model simulation suggests that this reduction of summer precipitation over eastern China can be attributed to a weakening of summer monsoon and a decrease of moisture vapor over tropical oceans caused by large volcanic eruptions.

1. Introduction

Volcanic forcing is an important natural cause of climate change on time scales ranging from days to centuries (Robock 2000). Large volcanic eruptions have significant impacts on land and ocean surface temperatures (Robock 2000; Church et al. 2005). Although the volcanic signals in precipitation are not as obvious as in temperature (Mass and Portman 1989; Robock and Liu 1994; Yoshimori et al. 2005), studies of observed and simulated global precipitation indicate that the volcanic signal is detectable (Allen and Ingram 2002; Gillett et al. 2004; Lambert et al. 2005; Trenberth and Dai 2007). Observational and proxy data indicated that volcanic eruptions might play an important role in summer precipitation changes over eastern China (Xu 1986; Shen et al. 2007, 2008). Xu (1986) found that northern China experienced droughts and the middle and lower Yangtze River valley saw floods in three colossal volcanic eruptions. Our previous studies suggested that large volcanic eruptions might play a role as a trigger in causing exceptional drought over eastern China (Shen et al. 2007) and that coherent droughts over eastern China are associated with large low-latitude volcanic eruptions (Shen et al. 2008). However, two key issues remain unresolved. First, are volcanic signals observed in proxy and observational data of regional precipitation also detectable in simulated precipitation? Second, what mechanism underlies the response of summer precipitation to large volcanic eruptions? Each of these two issues has implications for understanding the effect of large volcanic eruptions on regional climate and predicting climatic conditions following large volcanic eruptions. A climate model has been used to study the response of regional and global climate to individual large volcanic eruptions (e.g., Oman et al. 2005, 2006), to both tropical and Arctic aerosol precursor injection (Robock et al. 2008), and to

Corresponding author address: Caiming Shen, Atmospheric Sciences Research Center, University at Albany, State University of New York, 251 Fuller Road, Albany, NY 12203.
E-mail: cshen@climate.cestm.albany.edu

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TABLE 1. Eighteen cases of volcanic eruption with reduction in solar irradiance more than 8 W m^{-2}. VEI is the volcanic explosivity index.

Case No.	Volcano name	Location		Date	VEI
		Lat	Lon		
1	Unknown			1190	
2	Unknown			1196	
3	Unknown			1258	
4	Unknown			1276	
5	Unknown			1286	
6	Unknown			1345	
7	Kuwae, Vanuatu, southwest Pacific	16.8°S	168.5°E	1452	6
8	Huaynaputina, Peru	16.6°S	70.9°W	February 1600	6
9	Unknown			1621	
10	Parker, Philippines	6.1°S	124.9°E	January 1641	6
11	Halmahera, Indonesia	1.4°N	127.5°E	May 1673	5?
12	Unknown			1695	
13	Kilauea, Hawaiian Islands	19.4°N	155.3°W	November? 1790	4
14	Unknown			1810	
15	Tambora, Lesser Sunda Islands	8.3°S	118.0°E	April 1815	7
16	Babuyan Claro, Philippines	19.5°N	121.9°E	1831	4?
17	Krakatau, Indonesia	6.1°S	105.4°E	August 1883	6
18	Pinatubo, Luzon	15.1°N	120.4°E	June 1991	6

analogs of volcanic eruption such as nuclear explosions (e.g., Robock et al. 2007a,b). In this study, composite analyses are conducted to investigate the response of summer precipitation (May–September) over eastern China (25°–40°N, east of 105°E) to reductions in solar irradiance induced by large volcanic eruptions using a comprehensive 1000-yr climate simulation to provide insights on these issues.

2. Model simulations

To study the responses of precipitation to volcanic forcing, we analyze a 1000-yr simulation using the Community Climate System Model (CCSM, version 2.0.1) developed by the National Center for Atmospheric Research (NCAR; Kiehl and Gent 2004). The model comprises four components of the climate system: the atmosphere, ocean, land surface, and sea ice. These components are linked via a flux coupler without flux corrections. The atmospheric component is a primitive equation model with T31 in horizontal resolution (~3.75° in latitude and longitude) and 26 hybrid coordinate levels in the vertical. The land component has the same horizontal grid as the atmosphere and includes 5 different surface types (glacier, lake, wetland, urban, and vegetated) with 4–16 different vegetation types. The ocean component is the NCAR implementation of the Parallel Ocean Program (POP; Smith and Gent 2002) and has a longitudinal resolution of ~3.6° and variable latitudinal resolutions of ~1.8° and up to ~0.9° in the tropics. The sea ice component is a dynamic–thermodynamic model with same horizontal grid as the ocean component.

The 1000-yr simulation includes the following climate forcing: the global and seasonal change of the orbital insolation (Berger 1978), solar variations and volcanic eruptions (Crowley et al. 2003), and greenhouse gases (Ammann et al. 2007). Forcings due to changes in land cover/land use and tropospheric aerosols are not considered. In the simulation, the volcanic activity is represented as radiative forcing by multiplying the aerosol optical depth estimates derived from ice cores by a factor of −21 (Hansen et al. 2002) and applied as negative deviation from the solar constant. Note that all volcanic eruptions are timed to happen on 1 January. This approach of volcanic forcing was also employed by Bauer et al. (2003) and Yoshimori et al. (2005).

In this study, we focus only on the response of summer precipitation over eastern China to large volcanic eruptions, defined as the cases with reduction in solar irradiance more than 8 W m^{-2}. To facilitate the analysis, we also identify the year with the largest reduction in irradiance as the volcanic eruption year. For the case of consecutive years with more than 8 W m^{-2} reduction, the year with the largest reduction will be the year of eruption. In so doing 18 cases of volcanic eruption (Table 1) are selected through the simulation period of years 1000–1999.

A model–observation comparison indicated that the model simulates well the spatial pattern of summer precipitation over eastern China, although some difference exists in the simulated and observed total amounts of summer precipitation during the instrumental times (Shen et al. 2009). The time series of summer (May–September) mean precipitation over eastern China is calculated based on model data from the 1000-yr simulation. It is then used to examine the response of summer precipitation over eastern China to large volcanic eruptions. In this procedure, the superposed epoch analysis (SEA; Robock and Mao 1995) is employed. The SEA is a statistical method used to resolve a significant signal-to-noise problem (Adams et al. 2003). It is often applied to study on the relationship between climate and fire histories (e.g., Grissino-Mayer 1995; Schoennagel et al. 2005) and the relationship between volcanic activity and climate variations (Mass and Portman 1989; Adams et al. 2003). We ran SEA to assess if mean value of summer precipitation is significantly different during the volcanic eruption years relative to 5 pre- and post-volcanic eruption years. The composite patterns of heating budget, total precipitable water (TPW), and wind at 850 hPa for 18 cases of large volcanic eruption from the 1000-yr simulation are examined to understand mechanisms underlying the response of regional precipitation over eastern China to large volcanic eruptions.

3. Results

Figure 1a shows the results of SEA on modeled summer precipitation over eastern China for 18 cases of large volcanic eruption in 5 prevolcanic eruption years, the volcanic eruption year, and 5 postvolcanic eruption years. Summer precipitation over eastern China significantly decreases during the volcanic eruption year and the year after. Anomalies of summer precipitation are significantly lower than the mean at 95% and 90% confidence levels in the first and second year following volcanic eruptions. The largest reduction of summer precipitation appears in the volcanic eruption year, and the largest reduction occurs in its northeastern part (Fig. 1b). Summer precipitation returns to normal conditions 2 years thereafter. This temporal pattern in the response of precipitation to large volcanic eruptions is similar to that revealed by modeled and observed global precipitation (Gillett et al. 2004) and tropical precipitation (Robock and Liu 1994).

We analyze heating budget, total precipitable water, and wind at 850 hPa to understand mechanisms underlying the response of regional precipitation over eastern China to large volcanic eruptions. The summer composite means of surface latent heat flux, surface sensible heat flux, and TPW over midlatitude land and tropical oceans during the volcanic eruption year for 18 cases are shown in Table 2. Figure 2 shows their spatial patterns. The latent heat flux over land and ocean significantly decreases up to 1.18 and 1.15 W m^{-2}, respectively, during the volcanic eruption years. This fact suggests a clear decline of the evaporation in the tropical regions. A slight increase in the sensible heat flux is

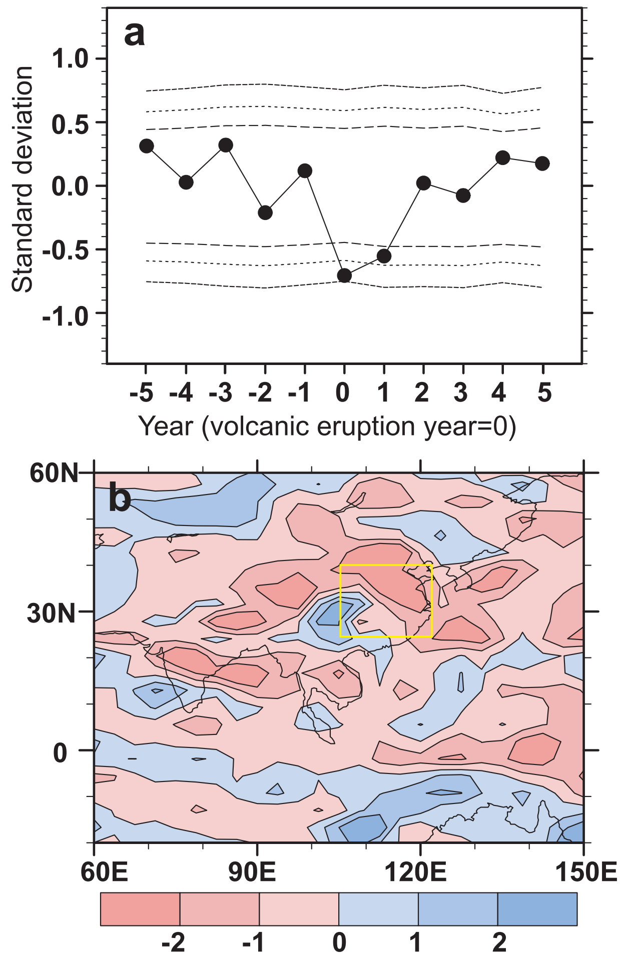

FIG. 1. (a) Results of superposed epoch analysis of modeled summer precipitation for 18 cases of large volcanic eruption showing the response of summer precipitation over eastern China. Bootstrapping procedures are used to assess the statistical significance of summer precipitation above and below the mean. The dashed and dotted lines represent confidence intervals of 90%, 95%, and 99% derived from 1000 Monte Carlo simulations. (b) Spatial pattern of composite anomalies of summer precipitation over East Asia and tropical oceans during the volcanic eruption year for 18 cases of large volcanic eruption; yellow box shows our study area.

observed over the tropical oceans, whereas a marked decrease occurs over eastern China. This implies the difference in the response of surface air temperature to large volcanic eruptions between ocean and land. The magnitude of the decline of surface air temperature over tropical oceans is smaller than that over land (Table 2). As expected, the TPW decreases markedly during the volcanic eruption years because of reduced evaporation over the tropical ocean. The largest reductions of TPW occur over the Indian and Pacific Oceans around 10°N, where the reduction of TPW is more than 1 kg m^{-2}. This result is consistent with Santer et al.'s (2007) study in

TABLE 2. Composite means of surface temperature (TS), surface sensible heat flux (SHF), surface latent heat flux (LHF), and total precipitable water (TPW) over midlatitude land and tropical oceans during the volcanic eruption year for 18 cases of large volcanic eruption.

Regions	TS (°C)	SHF (W m^{-2})	LHF (W m^{-2})	TPW (kg m^{-2})
Land (20°~60°N, 60°~150°E)	−0.61*	−0.16	−1.18*	−0.97*
Oceans (0°~20°N, 60°~150°E)	−0.37*	0.24*	−1.15*	−1.46*

* Significantly different from 1000-yr means at 95% confidence level.

which they identified a tropicswide decrease of precipitable water in phase 3 of the Coupled Model Intercomparison Project (CMIP3) simulations in response to volcanic eruptions. Reanalysis data also show a marked decline in TPW over eastern China in 1–2 years following large volcanic eruptions (Shen et al. 2007). The wind field at 850 hPa (Fig. 3) shows that both Indian and East Asian summer monsoons weaken during the volcanic eruption years. It is not unexpected since the heating contrast between ocean and land decreases during volcanic eruption years because of the difference in the response of surface air temperature over land and sea surface temperature to the reduction of irradiation caused by volcanic eruptions. This difference in response (larger over land than ocean) is likely due to the smaller effective capacity of the land compared to the ocean.

The primary moisture vapor for summer precipitation over eastern China originates from tropical oceans, especially the regions around 10°N (Park and Schubert 1997; Wang 2006). The moisture vapor is brought into eastern China by two airflows: the Indian summer monsoon and East Asian summer monsoon (Ding 1991; Wang 2006). It thus is evident that the significant reduction in summer precipitation over eastern China during a volcanic eruption year and the year after is caused by the decline of evaporation over tropical oceans and the weakening of both the Indian summer monsoon and East Asian summer monsoon.

Significant reductions in summer precipitation over eastern China during the volcanic eruption years are observed in our 1000-yr simulation, suggesting that reductions of solar irradiance due to large volcanic eruptions have detectable influences on summer precipitation over eastern China. This result is consistent with those observed from other model data and proxy data. Yu and Liu (2003) found that the annual precipitation over eastern China decreases if the stratospheric aerosol optical thickness at 550 nm is set at 0.15 in the GCM model of AGCM+SSIB [Simplified Simple Biosphere Model (SSIB)]. Shen et al. (2007) noted a statistically significant connection between explosive low-latitude volcanic eruptions and subsequent coherent drought over eastern China. The decrease in precipitation during the first 2 years following large volcanic eruptions is also found in other regions, such as tropical regions (Robock and Liu 1994), central and eastern United States (Portman and Gutzler 1996), and central Europe (Fischer et al. 2007). Having analyzed observed and modeled data, Robock and Liu (1994) hypothesized that reduced evaporation caused by tropospheric cooling results in reductions of tropical precipitation for 1–2 years following volcanic eruptions. Allen and Ingram (2002) also indicated that the energy balance of the troposphere controls global precipitation with latent heat of condensation balancing radiative cooling. Recently, a model study showed that the latent heat flux anomaly corresponds to reduced evaporation of about 0.1 mm day^{-1} in 3 years following the Mount Pinatubo eruption (Church et al. 2005), supporting this hypothesis. Our analyses show that the reductions of solar irradiance induced by large volcanic eruptions reduce the latent heat flux, and thus the evaporation over tropical oceans, which is the main moisture source of summer precipitation over eastern China due to troposphere cooling. It is evident that our results support this hypothesis too. On the other hand, our analyses also indicate that the reductions of solar irradiance induced by large volcanic eruptions weaken the strength of summer monsoon by which the moisture is brought into eastern China, resulting in a decline of summer precipitation in this region. Xu et al. (2006) noted that the declining trend of East Asian summer monsoon winds in the recent three decades may result from air pollution. Our results seem to support their speculation since volcanic eruptions have been suggested as an analog of anthropogenic stratospheric aerosol production.

4. Discussion

The climatic processes of volcanic eruptions are much more complicated than the idea that the effect of volcanic eruption is simply implemented as the reduction of global solar irradiance in our model. Furthermore, the time series of volcanic forcing used in our simulations has no information about seasonal and latitudinal distributions of the volcanic aerosols, which are potentially important components for attempting to realistically

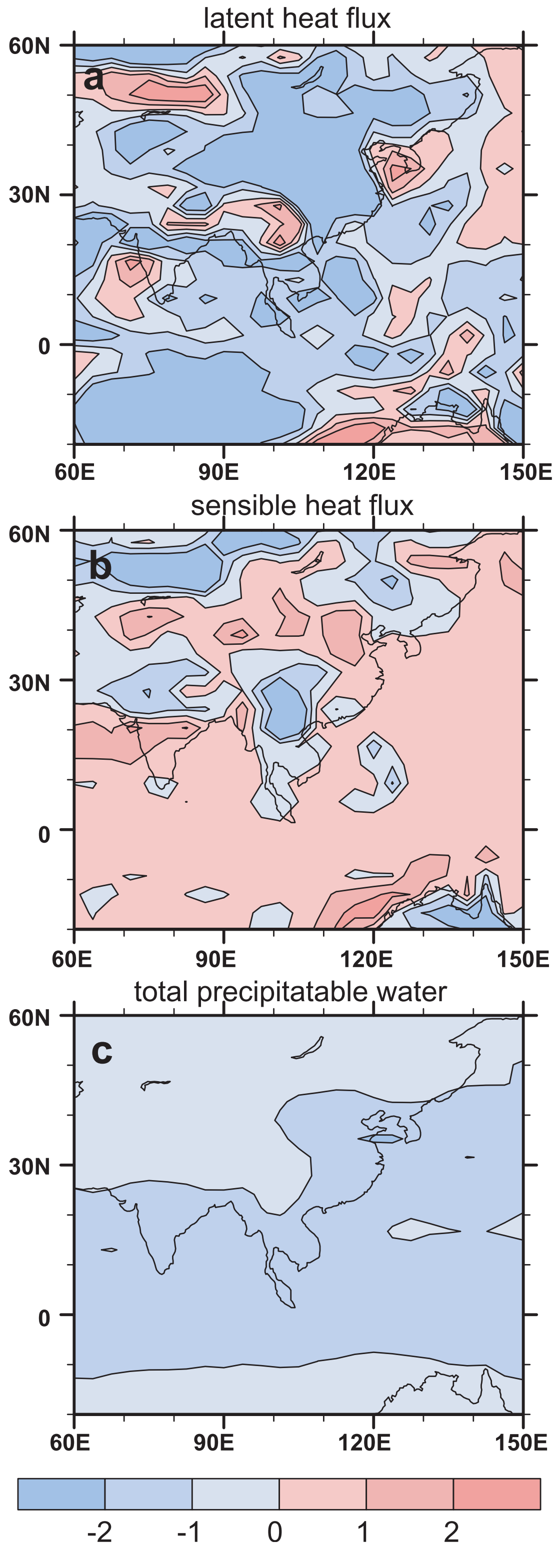

FIG. 2. Spatial patterns of composite anomalies of three climatic parameters in summer over East Asia and tropical oceans during the volcanic eruption year for 18 cases of large volcanic eruption: (a) surface latent heat flux (W m^{-2}), (b) surface sensible heat flux (W m^{-2}), and (c) TPW (kg m^{-2}).

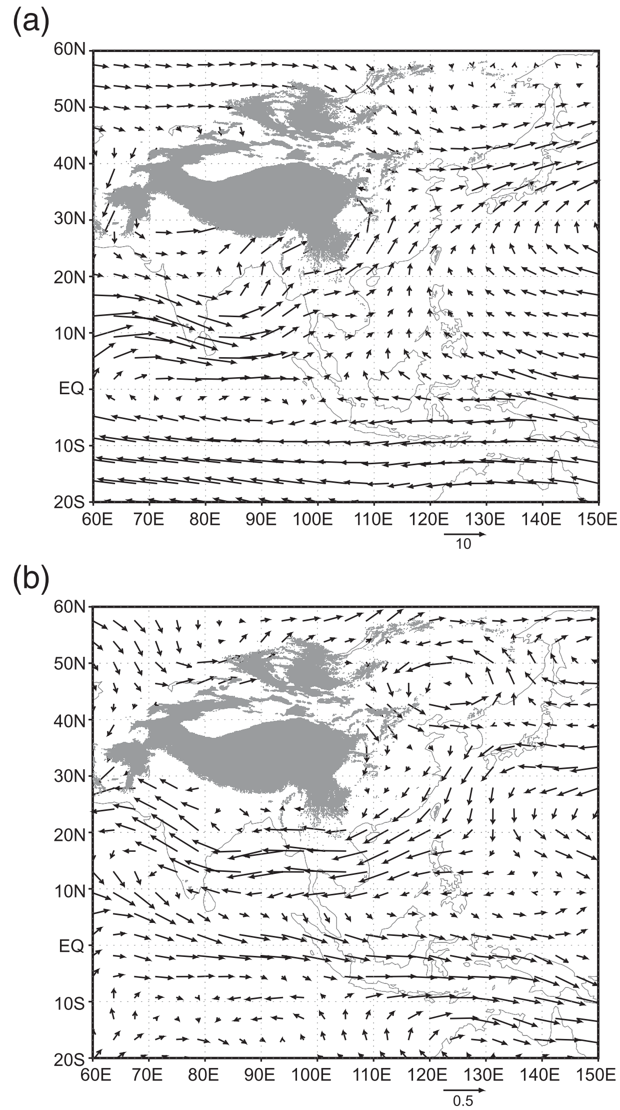

FIG. 3. (a) Spatial patterns of 1000-yr mean of wind at 850 hPa (m s^{-1}) in summer and (b) anomaly of composite mean of wind at 850 hPa (m s^{-1}) in summer from 1000-yr mean during the volcanic eruption year for 18 cases of large volcanic eruption.

simulate the perturbations. Timing and location of the volcanic eruption can affect the transport of aerosols into either hemisphere and thus affect the nature of the volcanic forcing on the climate (Ammann et al. 2003). For example, the analysis of proxy data indicates a statistically significant connection between explosive low-latitude volcanic eruptions and droughts over eastern China, whereas no significant connection occurs between summer precipitation over eastern China and explosive mid- to high-latitude volcanic eruptions (Shen et al. 2008). Therefore, the results presented here should be taken as a conceptual guideline toward an understanding of volcanic eruption effects on regional climate change.

Updated datasets of volcanic forcing are available now (Ammann et al. 2003; Gao et al. 2008), more simulations driven with the monthly and latitudinally volcanic forcing dataset are necessary for understanding more realistic effects of the volcanic aerosol on global and regional climate.

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