Wetter Global Arid Regions Driven by Volcanic Eruptions

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Abstract Arid regions are among the most sensitive areas to climate change; a better understanding of the impact of volcanic eruptions on the hydroclimate over global arid regions is helpful for adaptation but is not well studied. Here we show evidences that arid regions exhibit a wetter condition after volcanic eruptions based on reconstructions and observations, especially for volcanoes located in the Northern hemisphere and tropics. Such “dry gets wetter” response is further supported by climate model simulations driven by volcanic aerosol forcing. The dynamic processes related to changes in atmospheric circulation are found to play a dominant role in precipitation responses. The wetter condition over northern hemispheric (southern hemispheric) (NH (SH)) arid regions after southern (northern) hemispheric volcanic eruptions is caused by enhanced cross-equator flow, while the increased precipitation over global arid regions and NH (SH) arid regions following tropical volcanic eruptions and northern (southern) eruptions, respectively, are mainly controlled by the monsoon-desert coupling mechanism. The response of the extreme precipitation is consistent with that of the mean precipitation but more sensitive on a regional scale. The results indicate that volcanic eruptions at different latitudes should be considered in the design of near-term decadal climate prediction experiments and the implementation of geoengineering activities.

Plain Language Summary Investigation of the volcanic effect on the hydroclimate over arid regions is important to understanding the climate response to natural radiative forcing and is helpful for adaptation. However, our current knowledge in this regard is quite limited. For the first time, we analyzed the hydroclimate response over global arid regions to volcanic eruptions at different latitudes based on reconstructions over the last millennium, observations over the twentieth century, and climate model simulations. We found that the arid regions get wetter after different types of volcanic eruptions in both observations and simulations. By using quantitative diagnostic methods, the changes in circulation are considered to be the main cause. Precipitation responses after volcanic eruptions at different latitudes are attributed to different physical processes. Compared with the mean precipitation, the extreme precipitation responds more sensitively on a regional scale. This analysis has important implications for geoengineering and the near-term decadal climate prediction when considering the potential volcanic eruption at different latitudes in the design of experiments.

1. Introduction

Arid regions occupy approximately 41% of terrestrial land surfaces and are home to more than 38% of the world’s population, which are among the most sensitive areas to climate change and natural disasters (Huang, Li, et al., 2017; White & Nackoney, 2003). A better understanding of climate change and its response to radiative forcing in arid regions is helpful for adaptation. Previous studies have examined the precipitation response in arid regions to anthropogenic external forcing. Under high greenhouse gas (GHG) emissions, a drier climate is projected (Dai, 2013; Huang et al., 2016; Huang, Yu, et al., 2017). Anthropogenic aerosols and land use have small effects on averaged terrestrial aridity (Fu et al., 2016; Lin et al., 2016). Knowledge of the hydroclimate response to natural external forcing such as volcanic aerosol over arid regions is quite limited.

Volcanic eruptions, as one of the most important driving factor of natural climate variability, have significant impacts on the global hydroclimate (Robock, 2007; Timmreck, 2012). The sulfate aerosols in the stratosphere associated with volcanic eruptions can decrease the incoming shortwave solar radiation, resulting cooling of surface and suppressing the global hydrological cycle (Grinsted et al., 2007; Iles et al., 2013; Iles & Hegerl, 2014, 2015; Man et al., 2014; Oman et al., 2006; Paik & Min, 2017; Trenberth & Dai, 2007). In
the tropics, the climatologically wet regions show post-eruption drying, while the adjacent dry regions get wetter on average (Colose et al., 2016a; Iles et al., 2013; Iles & Hegerl, 2014, 2015). These responses are opposite to the “wet gets wetter, dry gets drier” precipitation response under global warming (Held & Soden, 2006) but are considered to be physically consistent with projections under global warming and are simply attributed to the thermodynamic effect (Colose et al., 2016a). In comparison to precipitation changes in the tropics and monsoon regions (Colose et al., 2016b; Haywood et al., 2013; Liu et al., 2016; Zhuo et al., 2014; Zuo et al., 2019), the physical processes for the precipitation response in the arid regions associated with volcanic eruption remains unknown. Extreme precipitation has larger impact on the society, but barely any efforts have been devoted to the study of extreme precipitation response to volcanic forcing.

In this study, we aim to reveal the hydroclimate responses to volcanic eruptions and the associated physical processes in the arid regions by combining the reconstructions, instrumental data, and Community Earth System Model Last Millennium Ensemble (CESM-LME) simulation. We focus on the mean precipitation changes but also extend the analysis to extreme precipitation.

The remainder of this paper is organized as follows: The data and methods are introduced in section 2. In section 3, we first show the hydroclimate response based on the reconstructions, observations, and model simulations and then analyze the mechanisms of precipitation responses by using diagnostic analysis methods. Finally, the conclusions are summarized in section 4.

2. Data and Methods

2.1. Reconstructions, Instrumental Data, and Model simulations

We used five reconstructions that extend from the past few centuries to 1000 years, including:

1. The Monsoon Asia Drought Atlas, a seasonally resolved gridded spatial reconstruction of Asian monsoon drought and pluvials over the past millennium (1300–2005) derived from tree-ring chronologies (Cook et al., 2010)
2. Palmer Drought Severity Index (PDSI) over the past 953 years in Morocco (Northwest Africa) derived from Cedrus atlantica ring width data (Esper et al., 2007)
3. Spatially and temporally highly resolved gridded reconstruction of precipitation over southern South America (Neukom et al., 2010), the summer and winter reconstructions back to 1498 and 1590, respectively
4. Eastern Oregon NOAA Climate Divisions 7 precipitation reconstructions from year 1705 to 1979, derived from tree-ring data by Gregg M. Garfin and Dr. Malcolm K. Hughes of the Laboratory of Tree-Ring Research, University of Arizona (Garfin & Hughes, 1996)
5. Reconstruction of precipitation in Turkey from 1628 to 1980 based on tree-ring data (chronologies of P.I. Kuniholm available from the International Tree-Ring Data Bank) (D’arrigo & Cullen, 2001)

Seven sets of monthly mean precipitation data covering the twentieth century with higher spatial resolution, the observed PDSI and Standardized Precipitation Evapotranspiration Index (SPEI) are also used, including:

1. The monthly mean precipitation data from the Global Precipitation Climatology Project data version 2.2 from 1979 to 2010 (Huffman et al., 2009)
2. The monthly mean precipitation data from the Global Precipitation Climatology Centre data from 1901 to 2013 with a spatial resolution of 0.5° × 0.5° (Schneider et al., 2014)
3. NOAA’s Precipitation Reconstruction over Land (PREC/L) from 1948 to 2011 with a spatial resolution of 0.5° × 0.5° (Chen et al., 2002)
4. Precipitation from the University of Delaware (UDEL, V4.01) from 1900 to 2014 with a spatial resolution of 0.5° × 0.5° (Willmott & Matsuura, 2001)
5. Variability Analysis of Surface Climate Observations (VASClimO’s monthly precipitation from 1951 to 2000 with a horizontal resolution of 2.5° × 2.5° (Beck et al., 2005)
6. Asian Precipitation—Highly Resolved Observational Data Integration Towards Evaluation (APHRODITE)’s daily gridded precipitation from 1951 to 2007 with a horizontal resolution of 0.25° × 0.25° (Yatagai et al., 2012)
7. Climate Research Unit (CRU) monthly precipitation dataset (V3.23) from 1901 to 2014 with a spatial resolution of 0.5° × 0.5° (Harris et al., 2014)
8. Global dataset of the Standardized Precipitation Evapotranspiration Index (SPEI, V2.4) based on CRU TS 3.23 precipitation and potential evapotranspiration data from 1901 to 2014 with a spatial resolution of 0.5° × 0.5° (Vicente-Serrano et al., 2010)

9. Self-calibrated Dai Palmer Drought Severity Index (PDSI) from 1850 to 2014 with a spatial resolution of 1.5° × 1.5° (Dai, 2011)

The CESM-LME simulations for 850–2005 are used in the present study (Otto-Bliesner et al., 2016). It provides the largest ensemble of last millennium simulations currently available and provides ensembles of simulations with each forcing individually. The volcanic forcing in CESM-LME is version 1 of the Gao et al. (2008) ice-core-derived reconstruction. As in Zuo et al. (2019), we used the data of five-member volcanic-only forcing experiments and constructed multimember means by averaging over all five volcanic-only forcing runs. Further details on the simulation are introduced in Otto-Bliesner et al. (2016).

2.2. Selection of Volcanic Events

We classify the volcanic eruptions into three types based on the distributions of volcanic aerosols in the Northern and Southern Hemispheres provided by Gao et al. (2008), viz., northern, tropical, and southern eruptions. The volcanic eruptions reaching their peaks at the same month are selected to remove the effect of eruption season. Different criteria are adopted for the model simulations and proxy dataset. For model simulation covering the period of 850–2005, the volcanic eruptions with intensity greater than the average are selected. The definition of average intensity of volcanic eruptions is the mean global total sulfate aerosol injection for all years when aerosol injection is not zero. For proxy and instrumental datasets which cover different time periods, we use a lower threshold of 5Tg (trillion gram) and 3Tg, respectively, to include more volcanic events. This criterion is the same as that in Zuo et al. (2019). The selected volcanic eruptions in model simulations and observations are shown in Table S1 and S2, respectively.

2.3. Definition of Global Arid Regions

The global arid domains are defined by the regions where the local summer precipitation rate less than 1.0 mm day$^{-1}$ following Wang et al. (2012). The local summer is denoted as MJJAS (May through September) for the Northern Hemisphere (NH) and as NDJFM (November through March) for the Southern Hemisphere (SH). We define the global arid region based on the 1979–2010 climatology from the Global Precipitation Climatology Project data version 2.2 (Adler et al., 2003). As shown in Figure 1a, the vast arid regions include southwestern United States, the west coast of South America, Central Asia, southwestern Africa, and Western Australia. The reconstructions and observations only cover terrestrial arid regions (red color in Figure 1a). In model simulation, we analyzed the arid regions over land and ocean (orange and red color in Figure 1a) in order to include more grid cells. The CESM-LME simulations reproduce the characteristics of global arid regions well (Figure 2), including the precipitation intensity and arid areas.

2.4. Super Epoch Analysis Method

As in Zuo et al. (2019), we used the “superposed epoch analysis (SEA)” method, which average the precipitation response to multiple volcanic eruptions to reduce internal variability (Adams et al., 2003; Anchukaitis et al., 2010; Haurwitz & Brier, 1981). We focus on the hydroclimate response in the first local summer after volcanic eruptions; the anomalies are calculated with respect to 5-year preeruption mean (Fischer et al., 2007; Iles et al., 2013). The significance of the response to volcanic eruptions was assessed using a Monte Carlo method. The details are given in the Supporting Information.

2.5. Removal of ENSO Effect

Following Iles et al. (2013) and Iles and Hegerl (2014), we used a linear regression method: $y' = y - r \times CTI$ to regress out the influence of ENSO in the observation; here $y'$ is ENSO-independent climate field, $y$ is the original climate field, and $r$ is the regression coefficient of winter ENSO index—cold tongue index (CTI) onto climate fields. The CTI is defined as the average sea surface temperature (SST) anomaly over the 6°N–6°S and 180°–90°W in the central-eastern Pacific. For the model simulation, the internal variability is removed through constructing multimember ensemble mean of the volcanic-only forcing experiment (Iles & Hegerl, 2014).
Figure 1. (a) Global distribution of arid regions for 1979–2010 climatology based on GPCP data, calculated following the definition in Wang et al. (2012). The red areas represent drylands, and orange areas represent arid regions over ocean. (b) Reconstructed hydroclimate response to northern, tropical, and southern volcanic eruptions in the first local summer over global arid regions, expressed as percentage changes relative to the climatology (units:%). Palmer Drought Severity Index response over Oregon; precipitation response over Turkey; PDSI response over arid regions of Asia; PDSI response over Morocco; and precipitation response over southern South America. (c) Hydroclimate responses in the first local summer following northern, tropical, and southern volcanic eruptions based on multiple observational datasets, including precipitation, SPEI, and PDSI, expressed as percentage of wet anomaly grids relative to the whole arid regions (units: %). The red, purple, and blue bars represent anomalies averaged over arid regions after northern, tropical, and southern volcanic eruptions. Thick lines show the multieruption mean, and the shading represents the spread between each volcanic eruption for (b) and the spread between each observation dataset for (c). The brown triangles represent arid regions.
2.6. Moisture Budget Analysis

To understand the mechanisms of precipitation changes over global arid regions after volcanic eruptions, a method of moisture budget analysis (Chou et al., 2009) is employed in this study. The anomalous precipitation can be decomposed as:

Figure 2. Comparison of precipitation climatology (1980–2005) between observation (GPCP) and CESM model: (a) local summer precipitation (mm day\(^{-1}\)) based on observation and (b) local summer precipitation (mm day\(^{-1}\)) based on CESM-LME simulation. The global arid domain (outlined by purple contours) in (a) and (b) is defined by regions where the local summer precipitation less than 1.0 mm day\(^{-1}\), where summer means MJJAS (NDJFM) for the NH (SH). The pattern correlation coefficient (PCC) between the observed and simulated global patterns is shown in (b).

Figure 3. Precipitation (units: mm day\(^{-1}\)) anomalies in the first local summer (MJJAS for northern hemispheric arid regions and NDJFM for southern hemispheric arid regions) following (a) northern, (b) tropical, and (c) southern volcanic eruptions based on CESM-LME simulation. The averaged responses over each subarid region after (d) northern, (e) tropical, and (f) southern eruptions. The significance levels are determined according to the Monte Carlo test, and the values that are significant at the 90% confidence level are dotted. The purple lines represent arid regions.
\[ P' = E' - \langle V_h' \nabla q' \rangle - \langle V_h' \nabla q \rangle - \langle \omega \bar{p} q' \rangle - \langle \bar{p} q \rangle + NL \]

where \( P \) and \( E \) represent anomalous precipitation and evaporation and \( q \) is the specific humidity. \( V_h' \) and \( \omega \) denote horizontal wind and vertical pressure velocity, respectively. The primes (′) indicate the departures from the climatology (\( \bar{\cdot} \)). Vertical integral \( <> \) denotes a mass integration through the troposphere with \( p_T \) as the depth of the troposphere. NL represents the sum of all nonlinear terms. Here, the terms only involve changes of specific humidity, and changes of vertical velocity are regarded as thermodynamic term and dynamic term, respectively. The details are given in the Supporting Information.

2.7. Quasi-Geostrophic Omega Equation Analysis

The quasi-geostrophic omega equation is used to diagnose the anomalous vertical motion in arid regions (Wei et al., 2014; Wei et al., 2017). The Laplacian of omega is balanced by the vertical differential of geostrophic absolute vorticity advection and the Laplacian of geostrophic temperature advection. The increased geostrophic absolute vorticity advection with height and warm advection will cause ascending motion. The level of 500 hPa is regarded as a nondivergence level and is most suitable for the analysis of vertical flows (Wei et al., 2014). Thus, we select 500 hPa to analyze the vertical flow and calculate each term of omega equation. The details are given in the Supporting Information.

3. Results

3.1. Hydroclimate Response in the Reconstructions

We first examine the hydroclimate response based on the reconstructions. To reveal the hydroclimate response to northern, tropical, and southern volcanic eruptions in global arid regions, we combine the results revealed by the precipitation and PDSI reconstructions. We found an overall wet anomaly in the arid regions of Oregon, Morocco, Asia, Turkey, and South America (Figure 1b). In Morocco and Asia, the PDSI has increased by more than 40% and three times, respectively. The wetting response is evident for all three types of volcanic eruptions but stronger for northern and tropical eruptions over most of the arid regions. Thus, the multiple sets of reconstructions reveal wetter conditions over most arid regions following all three types of volcanic eruptions. There are some regional differences in mean responses, which may be partly due to the different periods of reconstructions, the number of volcanoes, and also the quality of reconstructions (Table S3).

3.2. Hydroclimate Responses in the Observation

In order to examine the robustness of the findings based on proxy data and reveal the hydroclimate response in areas without reconstructions, we used six sets of instrumental precipitation data with higher resolution, observed PDSI and SPEI calculated based on instrumental meteorological elements to reveal drier/wetter conditions over arid regions after volcanic eruptions. The percentage of anomalous wet grid relative to total arid regions (anomalous wet grid/all grid over arid regions) is regarded as the hydroclimate response in the observation. Percentage greater than 50% that represents more than half of the region is getting wetter. We note that over arid regions located in Africa and South America, more than half of the arid region gets wetter after three types of volcanic eruptions (Figure 1c). About 50% of the arid
regions over Central Asia exhibit a wet anomaly following three types of volcanic eruptions. For arid regions over Northern America and Australia, wet anomalies are obvious after northern and tropical eruptions, respectively. To conclude, the observational datasets also indicate a wetter condition over global arid regions after three types of volcanic eruptions.

### 3.3. Hydroclimate Response in the CESM-LME Simulation

The precipitation responses to volcanic eruptions over the arid regions revealed by proxy and instrumental data are further demonstrated by model simulations, e.g., an overall wetter condition over global arid regions after three types of volcanic eruptions in the first local summer (Figures 3a–3c). The precipitation changes after northern eruptions exhibit a more uniform increasing anomaly than that after tropical and southern eruptions. Regional averages feature wetter conditions over all arid regions following northern eruptions (Figure 3d). Following tropical eruptions, the precipitation anomalies are characterized by the tendency for dry regions to become wetter except for the North America and South America arid regions, which might be caused by the uncertainty between different simulation members arising from the small land arid area and internal variability (Figure 3e). Following southern eruptions, drying is observed over the SH arid regions and wetting over the NH arid regions (Figure 3f). In general, the precipitation shows a positive anomaly over most arid regions after three types of volcanic eruptions.

To quantify the relative response, the changes are expressed as a percentage relative to the climatology of precipitation (Figure 4). The precipitation response to northern and southern eruptions is stronger than that to tropical eruptions. Specifically, northern (southern) eruptions can significantly increase precipitation in arid regions of the Southern (Northern) Hemisphere by ~14% (3%), while precipitation over arid regions of Southern (Northern) Hemisphere is increased by approximately 3% (1%) after tropical eruptions (Figure 4).

We also found that the response of surface runoff and net primary production (NPP) is similar to that of precipitation (Figure 5). Most arid regions show wetter conditions, especially following northern and tropical eruptions (Figure 5). In terms of percentage changes relative to the climatology of hydroclimate factors, the response of surface runoff and NPP is more sensitive than that of precipitation to volcanic eruptions over most arid regions (Figure 4) and the increase of runoff and NPP exceeds 4% and 7% over NH arid regions.
following northern eruptions, respectively, which is much higher than that of precipitation (2.3%). Hence the volcanic eruptions have significant impact on water resources and ecosystems over arid regions.

To reveal the extreme precipitation response with greater socioeconomic impact, we extend the analysis from mean precipitation to extreme events based on model simulation. Two extreme precipitation indices are selected. The first index is consecutive dry days (CDD) which is the maximum number of consecutive days with precipitation less than 1 mm; the second is consecutive wet days (CWD) which is the maximum number of consecutive days with precipitation larger than 1 mm. The results reveal a similar spatial response of extreme precipitation to mean precipitation. The increased CWD and decreased CDD indicate a wetter condition after volcanic eruptions (Figures 9a–9f), indicating that volcanic eruptions not only affect mean precipitation but also cause corresponding changes in extreme precipitation related to drought and flood hazards, which would cause widespread damages over fragile arid regions. Quantitatively, the increased CWD and decreased CDD are observed over most of the arid regions (Figures 6g–6i). But the extreme

Figure 6. Consecutive dry days (CDD) (units: days) and consecutive wet days (CWD) (units: days) anomalies in the first local summer following northern, tropical, and southern volcanic eruptions based on CESM-LME simulation. CDD response to (a) northern eruptions, (b) tropical eruptions, and (c) southern eruptions. CWD response to (d) northern eruptions, (e) tropical eruptions, and (f) southern eruptions. The averaged responses over each subarid region after (g) northern eruptions; (h) tropical eruptions; and (i) southern eruptions. The significance levels are determined according to the student’s t test, and the values that are significant at the 90% confidence level are dotted. Note that the shading in panels a–c represents CDD*1. The purple lines represent arid regions. For (g)–(i), CDD is multiplied by −1.
precipitation responds more sensitively than that of the mean precipitation on a regional scale. Specifically, the response of CDD is more sensitive in the NH arid regions (especially over Central Asia, features a 4.2% decrease) following northern eruptions, and the CWD responds more sensitively in the NH arid regions (especially over the North America) following southern eruptions, among which the changes in CWD over arid regions in southwestern United States exceeding 11% after southern eruptions.

3.4. Physical Mechanism to Precipitation Response: Diagnostic Methods

To understand the physical mechanism of precipitation response and quantify the contribution of thermodynamic and dynamic processes to the precipitation anomalies, we used the moisture budget analysis (Chou et al., 2009); quasi-geostrophic omega equation analysis is further used to reveal the underlying mechanisms behind the dynamic processes (Wei et al., 2014).

The moisture budget analyses show that the positive precipitation anomalies over the global arid regions after three types of volcanic eruptions are dominated by the circulation change ($-$ $<\omega \delta_p q>$) (Figures S1 and 7c). But the circulation responses to three types of volcanic eruptions is different, and the high-latitude eruptions cause significant changes in cross-equator flow (Figures S2b and 2e), which means the circulation responses in Northern Hemisphere and Southern Hemisphere after northern (southern) eruptions are different. However, tropical volcanic eruptions cause relatively uniform climate response globally; thus the cross-equator flow did not change significantly. Previous studies have also shown that volcanic eruptions in one hemisphere affect monsoon precipitation in the other hemisphere through different physical processes (Liu et al., 2016; Zuo et al., 2019). Therefore, we analyzed the mechanism of precipitation response in arid regions after each type of volcanic eruption according to the following logic. The response of precipitation in arid regions after tropical eruptions is studied as a whole since tropical eruptions cause uniform climate responses globally. The precipitation responses to northern and southern eruptions are divided into two parts: precipitation responses in one hemisphere to volcanic eruptions in the same hemisphere and the other hemisphere, respectively.

3.4.1. Increased Precipitation in NH (SH) Arid Regions Induced by Southern (Northern) Volcanic Eruptions

For the increased precipitation in NH (SH) arid regions induced by southern (northern) volcanic eruptions, the moisture budget analyses show that the positive precipitation anomalies over the NH (SH) arid regions are dominated by the positive anomalous advection of the climatological vertical moisture by ascending anomalies ($-$ $<\omega \delta_p q>$), while the anomalous advection of the vertical moisture anomaly by climatological descending motion ($-$ $<\omega \delta_q q>$), the horizontal moisture advection anomalies ($-$ $<V \cdot \nabla q>$) and evaporation have small contributions (Figures 7a and 7b). The changes in vertical motion thus play a dominant role in increased precipitation. What kind of processes has dominated the vertical motion changes? The quasi-geostrophic omega equation analysis reveals that term $v_g \frac{\partial T}{\partial y}$ is the primary contributor to anomalous vertical motion, which represents the mean temperature advection by anomalous meridional wind. The anomalous meridional temperature advection components at 500 hPa over NH (SH) arid regions in boreal summer (winter) after southern (northern) eruptions reveals a warm temperature advection, which
results from the negative (positive) climatological meridional temperature gradient in the NH (SH) midlatitudes during the boreal summer (winter) and anomalous southerly (northerly) wind over NH (SH) arid regions. Where does the anomalous southerly (northerly) wind over NH (SH) arid regions come from? We further show the cross-equator flow response to three types of eruptions (Figure S3), which is also proved in Zuo et al. (2019) regarding the global monsoon response to volcanic eruptions. The anomalous meridional winds show a weakened cross-equator flow after northern volcanic eruptions (see Figure S3a) and a strengthened cross-equator flow following southern volcanic eruptions (see Figure S3b). The low-level circulation response in SH arid regions to northern eruptions together with the climatological surface temperature is shown in Figure S4; the climatological temperature has a positive

Figure 8. (a) Spatial pattern for the anomalous meridional temperature advection components (units: $10^{-6} \text{K} \cdot \text{s}^{-1}$) at 500 hPa in boreal summer (MJJAS) after southern eruptions. (b) Spatial pattern for the anomalous meridional temperature advection components (units: $10^{-6} \text{K} \cdot \text{s}^{-1}$) at 500 hPa in austral summer (NDJFM) after northern eruptions. (c) Zonal circulation anomaly averaged over 10°–45°N in boreal summer following tropical eruptions (units: m s$^{-1}$). The green and brown colors represent the Asian monsoon region and the adjacent arid region, respectively. The black areas indicate the maximum elevation along 0°–180°E and 10°–45°N.
meridional gradient in the SH arid regions, so the anomalous northerly wind component associated with strengthened cross-equator flow advects warm air into the SH arid regions. The warm advection further leads to the anomalous ascending flow over NH (SH) arid regions following southern (northern) eruptions (Figures 8a and 9b).

3.4.2. Increased Precipitation in Global Arid Regions Induced by Tropical Volcanic Eruptions

For the increased global precipitation in arid regions induced by tropical volcanic eruptions, the analyses show that the increased precipitation is mainly dominated by positive anomalous advection of climatological vertical moisture by ascending anomalies ($-\omega \bar{\delta} \rho q'$), whereas the evaporation has a negative contribution, the positive anomalous advection of anomalous vertical moisture by climatological descending motions ($-\omega \bar{\delta} \rho q'$) and the horizontal moisture advection anomalies ($-V \cdot \nabla q'$) have relatively small contributions (Figure 7c). While the thermodynamic term related to changes in specific humidity has contribution to the increased precipitation through weakened moisture divergence over climatologically descending arid regions, more than 50% of the increased precipitation is balanced by the dynamic term related to changes in circulation (Figure 7c).

In addition to local effects, hydroclimate changes over arid region can also be influenced by remote changes via the "monsoon-desert coupling mechanism" (Rodwell & Hoskins, 1996, 2001; Wang et al., 2012). The diabatic heating over monsoon regions induces a westward Rossby wave, which interacts with subtropical westerlies and induces descending motion over the adjacent arid regions. Wang et al. (2012) also used this mechanism to explain the wetter monsoon region and the drier arid region under global warming. Since Zuo et al. (2019) analyzed the global monsoon precipitation response to tropical volcanic eruptions and found that the anomalous descending motion caused decreased precipitation over monsoon regions, we analyzed whether this mechanism also played a role in the precipitation response in monsoon and arid regions after volcanic eruptions. The zonal circulation anomaly averaged over 10–45°N following northern eruptions shows a secondary circulation over the Asian region, with descending motion over the Asian monsoon region and ascending motion over the adjacent arid region (Figure 8c).

The decrease of precipitation and associated latent heat over the Asian monsoon region after tropical eruptions induce a weakened westward Rossby wave finally leads to a cyclone in the upper levels and an anticyclone in the lower levels (Figure S5). Hydrostatic balance requires that there must be a shoaling of the isentropic surface, which will interact with the midlatitude westerlies and cause the ascending motion over arid regions through the monsoon-desert mechanism (Rodwell & Hoskins, 1996).

3.4.3. Increased Precipitation in NH (SH) Arid Regions Induced by Northern (Southern) Volcanic Eruptions

For the increased precipitation in NH (SH) arid regions induced by northern (southern) volcanic eruptions, the moisture budget shows that the increased precipitation is mainly balanced by positive anomalous advection of climatological vertical moisture by ascending anomalies ($-\omega \bar{\delta} \rho q'$), which is related to changes in vertical motion (Figures 9a and 9b). Take the response over NH arid regions as an instance, we found that the circulation change shows a secondary circulation over the Asian region, which is also controlled by the monsoon-desert mechanism (Figure 9c).
4. Summary and Concluding Remarks

We examined the hydroclimate responses of global arid regions after volcanic eruptions at different latitudes based on reconstructions, observations, and CESM-LME simulations. The schematic diagram of hydroclimate responses to different volcanic eruptions is depicted in Figure 10. Main findings are summarized below.

(1) Large sets of hydroclimate reconstructions reveal enhanced precipitation over global arid regions after volcanic eruptions, particularly after northern and tropical eruptions. Such response is also evident in the results derived from multiple sets of observations and is further supported by the volcanic-only forcing experiment of CESM-LME simulations.

(2) To reveal the physical mechanisms of anomalous precipitation, a method of moisture budget analysis and quasi-geostrophic omega equation are employed. We found the dynamic processes, which are related to changes in atmospheric circulation, play a prominent role in precipitation responses. The wetter condition over the SH (NH) arid regions after northern (southern) volcanic eruptions is primarily due to the warm advection induced by increased hemispherical thermal contrast. The global arid regions and NH (SH) arid regions become wetter following tropical eruptions and northern (southern) eruptions, respectively, which are mainly controlled by the monsoon-desert coupling mechanism.

**Figure 10.** Schematic diagram of hydroclimate responses over arid regions following volcanic eruptions at different latitudes: precipitation and low-level wind anomaly (vector) over arid regions in the first local summer after (a) northern, (b) tropical, and (c) southern eruptions. \( -<\omega \delta q > > 0 \) denotes that the dynamic processes related to changes in atmospheric circulation play a dominant role in precipitation responses. The purple and blue ellipses denote the surface cooling over the different hemisphere. Positive precipitation anomalies are denoted by green color.
(3) The responses of extreme precipitation and mean precipitation to volcanic eruptions resemble each other, but the extreme precipitation responds more sensitively than that of the mean precipitation on a regional scale. Although the increased mean precipitation is beneficial to water resources, the increased extreme precipitation accompanied by severe flooding would cause widespread damages over the arid region. The response of surface runoff and NPP also exhibits similar characteristics to that of the precipitation but with stronger intensity, which indicates a significant impact of volcanic eruptions on changes in water resources and ecosystems.

Zuo et al. (2019) investigated the hydroclimate responses over global monsoon regions to volcanic eruptions at different latitudes and found that the monsoon precipitation in one hemisphere is enhanced (reduced) by the volcanic forcing in the other (same) hemisphere, which results from enhanced cross-equator flow and decreased land‐sea thermal contrast, respectively. Compared with the precipitation response over global monsoon region, the global arid regions become wetter after all three types of volcanic eruptions, which is quite different from that of the monsoon region. Although the arid regions feature a wetter condition after three types of volcanic eruption, they are attributed to different physical processes—strengthened cross-equator flow and the monsoon‐desert coupling mechanism. It is worth mentioning that there is an increased precipitation in both monsoon and arid regions of NH (SH) after southern (northern) eruptions, indicating that the influence of cross-equator flow is more dominant than that of the monsoon‐desert mechanism when considering the response to remote volcanic forcing occurring in the other hemisphere.

To conclude, it is thus imperative to consider the potential volcanic eruption at different latitudes in the design of near‐term decadal climate prediction experiments such as the Decadal Climate Prediction Project (DCPP) for the 6th Coupled Model Intercomparison Project (CMIP6) (Boer et al., 2016). Meanwhile, attention should be paid to the divergent effects of stratospheric aerosol injected into different latitudes based on geoengineering (Kravitz et al., 2015).

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References


