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Key Points:

- Monsoon climate regions are highly sensitive to volcanic direct radiative and posteruption circulation changes
- A significant portion of the posteruption temperature and precipitation anomalies over African and South Asian convective regions is characterized by posteruption variation in El Niño-Southern Oscillation in summer season
- Quantification of volcanic-induced direct radiative and circulation impacts is important for better understanding of the climatic regime of monsoon regions

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Regional Climate Response of Middle Eastern, African, and South Asian Monsoon Regions to Explosive Volcanism and ENSO Forcing

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Abstract It is well observed that the monsoon climate experiences substantial climatic changes following explosive volcanism. Likewise, previous studies show that the monsoon climate regimes, especially, the African and South Asian tropical regions, are adversely affected by El Niño-Southern Oscillation (ENSO) events. Hence, studying the sensitivity of the monsoon regions to the effect of these forcing factors, that is, explosive volcanism and volcanic-induced ENSO forcing, is essential for better understanding the driving mechanism and climate variability in these regions. Using observations and a high resolution atmospheric model, effectively at 50- and 25-km grid spacing, this study shows that ENSO and tropical eruptions together weaken the upward branch of Northern Hemisphere (NH) Hadley cell, that is, Intertropical Convergence Zone. This results in a significant decrease of monsoonal precipitation, suggesting severe drought conditions over the NH tropical rain belt regions. The volcanic-induced direct radiative cooling and associated land-sea thermal contrast result in significant warming and drying due to the reduction of clouds over the monsoon regions in boreal summer. The posteruption ENSO circulation also results in warming and drying over NH tropical rain belt regions. This study confirms that the monsoon climate regime responds vigorously to posteruption direct radiative and indirect circulation impacts caused by volcanic-induced ENSO forcing. Hence, quantification of magnitude and spatial pattern of these postvolcanic direct and indirect climatic responses is important for better understanding of climate variability and changes in Asian and African monsoon regions.

1. Introduction

Climatic impacts of explosive volcanic eruptions are getting valuable attention due to their strong association with global warming slowdown. Volcanic eruptions act as an important driving factor for natural climate variability (Fyfe et al., 2013; Santer et al., 2014; Schneider et al., 2009; Timmreck, 2012). Large explosive eruptions inject an enormous amount of sulfur-containing gases into the lower stratosphere, where they are transported around the globe by general circulation. These gases oxidize to sulfuric acid aerosols plume that reflects the downwelling solar radiation and varies weather and climate patterns for two to three posteruption years (Mitchell, 1961; Lamb, 1970; Robock & Mao, 1995; Robock, 2000, 2002). A comprehensive overview of volcanic-induced climatic interactions can be seen in the past reviews (Briffa et al., 1998; Hansen et al., 1992; Kelly et al., 1996; Kremser et al., 2016; Laakso et al., 2016; Robock, 2000; Sigurdsson, 1982; Timmreck, 2012; Turco et al., 1982). Volcanic eruptions drastically affect both global and regional climate (Schneider et al., 2009; Timmreck, 2012).

Previously, the radiative impacts of tropical, low-latitude and high-latitude eruptions are widely discussed, especially their effect on monsoon regions (see, e.g., Mukherjee et al., 1987; Zambri & Robock, 2016; Oman et al., 2005, 2006; Trenberth & Dai, 2007; Anchukaitis et al., 2010; Joseph & Zeng, 2011; Haywood et al., 2013; Wegmann et al., 2014; Man et al., 2014; Liu et al., 2016; Dogar et al., 2017; Dogar, 2018). Most of the past studies on volcanism have shown volcanic impacts after removing or without considering the impact of El Niño-Southern Oscillation (ENSO) teleconnection (D'Arrigo et al., 2009; Joseph & Zeng, 2011; Oman et al., 2006; Robock & Mao, 1995; Santer et al., 2014; Trenberth & Dai, 2007). Interestingly, recent studies have revealed a strong connection between ENSO and explosive eruptions, suggesting that eruptions may induce El Niño (Pausata et al., 2015, 2016) or La Niña (D'Arrigo et al., 2009; McGregor & Timmermann, 2011) like anomalies. It has been discussed in numerous studies that explosive volcanic

eruption provides suitable conditions that may trigger ENSO phenomenon (Emile-Geay et al., 2008; Liu et al., 2018; Liu et al., 2018; Maher et al., 2015; Ohba et al., 2013; Predybaylo et al., 2017). Moreover, studies have also indicated that ENSO impacts are very important, especially in the monsoon regions (Ashok et al., 2004, 2007; Azharuddin & Dogar, 2016; Dogar et al., 2017; Dogar et al., 2018; Shukla, 1975). By employing global climate model simulations (Almazroui et al., 2017) and observational/reanalysis products, it has been examined that ENSO teleconnection produces strong impact over the Arabian Peninsula summer rainfall (Abid et al., 2018). The ENSO strongly impacts the Hadley cell (HC), especially the upward branch of HC that is strongly coupled to the monsoon system. It has been shown that the positive phase of ENSO produces weakening to African, Middle Eastern, and South Asian summer monsoon system, whereas the reverse is generally observed for La Niña phase (Dogar, Kucharski, & Azharuddin, 2017; Dogar et al., 2018; Roxy et al., 2015). Earlier studies have also emphasized that the ENSO and volcanic forcing (e.g., El Chichón and Pinatubo) effectively modulate the temperature and precipitation patterns across the globe, especially in the tropics (Gu & Adler, 2012; Gu & Adler, 2011). Therefore, it is imperative and has great importance to discuss and analyze the combined impacts of ENSO and volcanism, especially over the monsoon climate regions.

Literature review summarized above clearly indicates that monsoon climatic regime is highly sensitive to explosive volcanism and ENSO forcing resulting in a need to study the combined impact of ENSO and volcanic forcing to better understand climatic changes over these regions. In this paper, we will assess the sensitivity of Middle East and Africa (MEA) and South Asian summer climate to volcanic-induced radiative perturbations and will see how posteruption leading ENSO teleconnection pattern affects these regions. Hence, the aim of this study is to better understand and assess the regional climatic response and sensitivity of Middle East, Africa, and South Asia to large explosive volcanic eruptions in summer season.

For this purpose we used an atmospheric model with a very fine spatial resolution, effectively at 50- and 25-km grid spacing, typically comparable to the resolutions of regional climate models, and simulated the radiative and circulation effects of recent well-observed volcanic events over Middle East, African, and South Asian monsoon regions. The use of high-resolution modeling technique provides us a unique opportunity to examine how the volcanic-induced circulation anomalies at various scales influence regional climate. To the best of our knowledge, there is rarely any study pertaining to regional volcanic impacts using a Global Climate Model (GCM) at a spatial resolution of about 50 to 25 km or better; hence, in this sense this study is very useful for its successors. Besides, this version of HIRAM GCMs are effective in overcoming many of the limitations encountered by coarse-resolution GCMs and Regional Climate Models (RCMs). Due to their fine grid spacing, important processes such as large-scale condensation, land-sea interaction, and topographical forcing are better resolved in high-resolution GCMs (Boyle & Klein, 2010; Lau & Ploshay, 2009; Harris et al., 2016). Recent studies further emphasized that the regional convective structure and precipitation change are very sensitive to the model horizontal resolution (Bui et al., 2019; Liu, Yu, & Chen, 2018). HIRAM model has been previously used effectively to simulate aerosol's direct radiative and circulation impacts (Bangalath & Stenchikov, 2015; Dogar, 2018; Dogar & Sato, 2018; Dogar & Shahid, 2018; Dogar, Stenchikov, et al., 2017; Osipov et al., 2016). The idea of choosing two different HIRAM resolutions is to see if there could be any improvement in the simulations of volcanic impacts with improved resolution.

We focus on well-observed tropical eruptions of the late twentieth century, El Chichón of 1982 and Pinatubo of 1991. Both these eruptions have better observational records, which provide us an opportunity to validate the simulation results. We focus on the following questions.

1. What are the combined effects of volcanic eruptions and ENSO teleconnection over African and South Asian monsoon regions?
2. What is the direct radiative and indirect circulation impact of volcanism over Middle East, Africa, and South Asia?
3. How well HIRAM, a high-resolution atmospheric model, can reproduce posteruption direct radiative and circulation changes over monsoon regions in summer?

It is worth mentioning that HIRAM model reflects fairly well to volcanic forcing (Dogar, 2018; Dogar, Stenchikov, et al., 2017) and associated changes at the surface, and the lower stratosphere. This study aims to better understand the regional climatic impacts of volcanism and volcano-induced ENSO forcing over the monsoon-fed regions; therefore, we focused on the surface responses rather than the stratospheric

responses. The impact of these eruptions in the stratosphere has been widely discussed in previous studies (see, e.g., Stenchikov et al., 2002, 2004, 2006; Angell, 1991, 1993, 1997; Angell et al., 1996; Fujiwara et al., 2015).

The rest of the paper is organized as follows. Section 2 describes the climate model in conjunction with data and methodology. Section 3 presents results and discussion, which includes a detailed overview of total impacts and posteruption direct radiative impacts along with posteruption ENSO impacts. In the last section, we summarize our results.

2. Material and Methods

2.1. Model Description and Experiment Setup

To study regional climate responses caused by a global-scale volcanic forcing and modulated by interaction of local and global processes, we employed high-resolution simulations conducted using the Geophysical Fluid Dynamics Laboratory (GFDL)'s global High-Resolution Atmospheric Model (HiRAM) at 25- and 50-km grid spacing, typically a range that most of the regional climate models use in climate downscaling studies. This version of the HIRAM model is based on Atmospheric Model version 2 of GFDL (AM2; Anderson et al., 2004) with increased horizontal and vertical resolutions. The model has a top at 10 hPa with 32 vertical layers instead of 24, as well as simplified parameterizations (Zhao et al., 2009). HIRAM uses new cubed-sphere finite-volume dynamical core (Putman & Lin, 2007). However, it retains the surface flux, gravity wave drag, land surface, boundary layer, radiative transfer modules, and large-scale cloud microphysics of AM2 (Zhao et al., 2009). The shortwave (SW) radiation algorithm used by HIRAM follows Freidenreich and Ramaswamy (1999). The longwave (LW) radiation code follows Schwarzkopf and Ramaswamy (1999). The high-resolution experiments used in this study allow us to study regional climatic changes using a global model that fully accounts for regional- and global-scale interactions, which are especially important in the tropics. In these simulations, HIRAM model is run in Atmospheric Model Intercomparison Project (AMIP) style. It is forced with prescribed sea surface temperature (SST) and sea ice boundary conditions (Rayner et al., 2003). The anthropogenic greenhouse gases, ozone, natural forcings, land use, and tropospheric aerosol concentration employed in the model follow the AMIP experimental setup. The volcanic stratospheric aerosol spatial-time distribution and optical characteristics used in this model for El Chichón and Pinatubo eruptions are calculated following Stenchikov et al. (2006) based on Sato et al. (1993). This volcanic aerosol forcing data set provides zonally averaged, monthly mean spectral-dependent aerosol extinction, single-scattering albedo, and asymmetry parameters. The indirect effect of aerosols through interaction with clouds and associated changes in cloud properties is not considered. The AMIP-style simulation setup considered in HIRAM simulations is described in detail at http://cmip-pcmdi.llnl.gov/cmip5/guide_to_cmip5.html and <https://www.gfdl.noaa.gov/cmip>. The model was run for the period 1976–2008, which covers Northern Hemispheric El Chichón and Pinatubo eruptions. We focused on the late twentieth century's Northern Hemispheric tropical eruptions only. The Agung eruption is also coincided with the El Niño event; however, it is not considered, as it is a Southern Hemispheric tropical eruption, and its climatic response, primarily, the posteruption Intertropical Convergence Zone (ITCZ) response appears to be different from the Northern Hemispheric tropical eruptions (Haywood et al., 2013; Liu, Xing, et al., 2018). The first 3 years of integration are not used in order to avoid spin-up effects. Three different realizations, each started with a different initial condition, are conducted. To reduce the uncertainty in the model results, we have conducted ensemble average over these three HIRAM realizations correspondingly each for 50 and 25 km. The HIRAM at 50-km/25-km horizontal resolution share the same primitive equations, cubed sphere finite volume dynamical core, and physical parameterization schemes. The main difference among these model versions is the improved horizontal resolution (i.e., doubled the horizontal resolution). More details of HIRAM with 50- and 25-km horizontal grid spacing can be seen in Zhao et al. (2009) and Chen and Lin (2011), respectively. HIRAM has been used previously to study volcanic and dust aerosol impacts (Bangalath & Stenchikov, 2015; Dogar, 2018; Dogar, Stenchikov, et al., 2017; Stenchikov & Dogar, 2012). A detailed description of the HIRAM model, including its different components (e.g., atmospheric and land and sea ice model component) and relevant references regarding the changes, made compared to previous GFDL's atmospheric models are available at <https://www.gfdl.noaa.gov/hiram/>.

2.2. Data and Methodology

For comparison and validation of the model results, University of Delaware (UDEL) monthly global gridded high-resolution ($0.5^\circ \times 0.5^\circ$ horizontal grid) data of air temperature and precipitation fields is used (Legates & Willmott, 1990).

Initially, we showed combined/total anomalous signal that contains both postvolcanic direct radiative and indirect dynamic circulation impacts, and afterward, we analyzed posteruption circulation impacts and volcanic direct radiative impacts separately that are computed using multiple regression technique (section 3.2). Multiple regression technique has been widely used to separate the volcanic signal and other major variability modes (see, e.g., Randel, 2010; Fujiwara et al., 2015; Dogar & Sato, 2018; Gu & Adler, 2010; Gu & Adler, 2011). Nonetheless, some shortcomings of using regression are possible as the climate system is complex (Mitchell et al., 2014). The ideal/best approach to identify the direct volcanic and posteruption ENSO response is by conducting climate model sensitivity experiments with and without volcanic aerosol forcing (e.g., Predybaylo et al., 2017). This study is to a great extent based on the comparison of our model simulations with observations that do not have nonvolcano realizations. That is why we conducted the model analysis similar to our analysis of observations and did not include the nonvolcanic or non-ENSO control simulations. These are AMIP-style runs, in which the ENSO state is prescribed. It is not the goal of this paper to determine whether volcanoes cause ENSO, which would require a fully coupled model. Using an atmospheric model forced with the prescribed SST is, of course, an idealized approach but a fairly reasonable one, as demonstrated in previous studies (Dogar, Stenchikov, et al., 2017; Stenchikov et al., 2004, 2002). The ocean effect in our simulations is not interactive, but it is present. The observed SST forcing, used in the calculations, accounts for the ocean's response to volcanic forcing. It allows us to correctly account for such aspects of natural variability as El Niño at the time of the eruption. Thus, in our simulations, the atmospheric response is fully interactive and constrained by observed ocean boundary conditions. This approach allows us to evaluate the contributions of different processes more reliably and compare our results with observations.

A two-tailed Student's local t test is applied to find statistical significance of posteruption climate responses at 95% confidence level both in the model and observations. We have analyzed two posteruption summer (June–July–August, JJA) seasons. Simulated and observed anomaly patterns considered in the analysis are calculated as a seasonal departure from the mean summer season climatology of 30 years (1979–2008) that is computed after excluding at least two posteruption summer seasons.

Volcanic impacts are short-lived, causing signals with relatively low signal-to-noise ratio. The Superposed Epoch Analysis (SEA) is generally used to resolve this signal-to-noise problem. This is especially desired in cases where the responses to particular events (in our case large radiative forcing from explosive volcanic eruptions) may be disguised by noise from other competing influences that operate at similar time scales (e.g., internal variation). Through simple compositing, the SEA method involves sorting data into categories dependent on a *key date* for synchronization and then using the means of those categories. Therefore, to reduce the noise due to internal variability and making the volcanic signal clearer, we applied SEA (composite analysis) and combined the climate responses for both the eruptions and for two posteruption summer seasons (see, e.g., Schneider et al., 2009; Haurwitz & Brier, 1981; Peng et al., 2010). Compositing methodology is widely used for studying the effect of volcanoes on climate (Dogar, Stenchikov, et al., 2017; Fischer et al., 2007; Iles et al., 2013; Peng et al., 2010; Schneider et al., 2009; Sigl et al., 2015; Stenchikov et al., 2006). The SEA is applied both on the observations and model results. Each composite is composed of four summer seasons following El Chichón and Pinatubo eruptions (i.e., 1982, 1983, 1991, and 1992). The simulation results averaged over three HIRAM realizations compare well with the observations that lend support to the robustness of modeling results; however, we anticipate that adding more realizations might further improve the robustness. We tested the statistical significance by using the bootstrapping approach as well (not shown); however, it gave almost similar pattern as obtained using Student's t test.

3. Results and Discussion

3.1. Temperature and Precipitation Response

Earlier studies have emphasized that stratospheric volcanic aerosols induce perturbations to the radiative forcing (Hansen et al., 1997; Ramaswamy et al., 2001) that result in significant global- and regional-scale

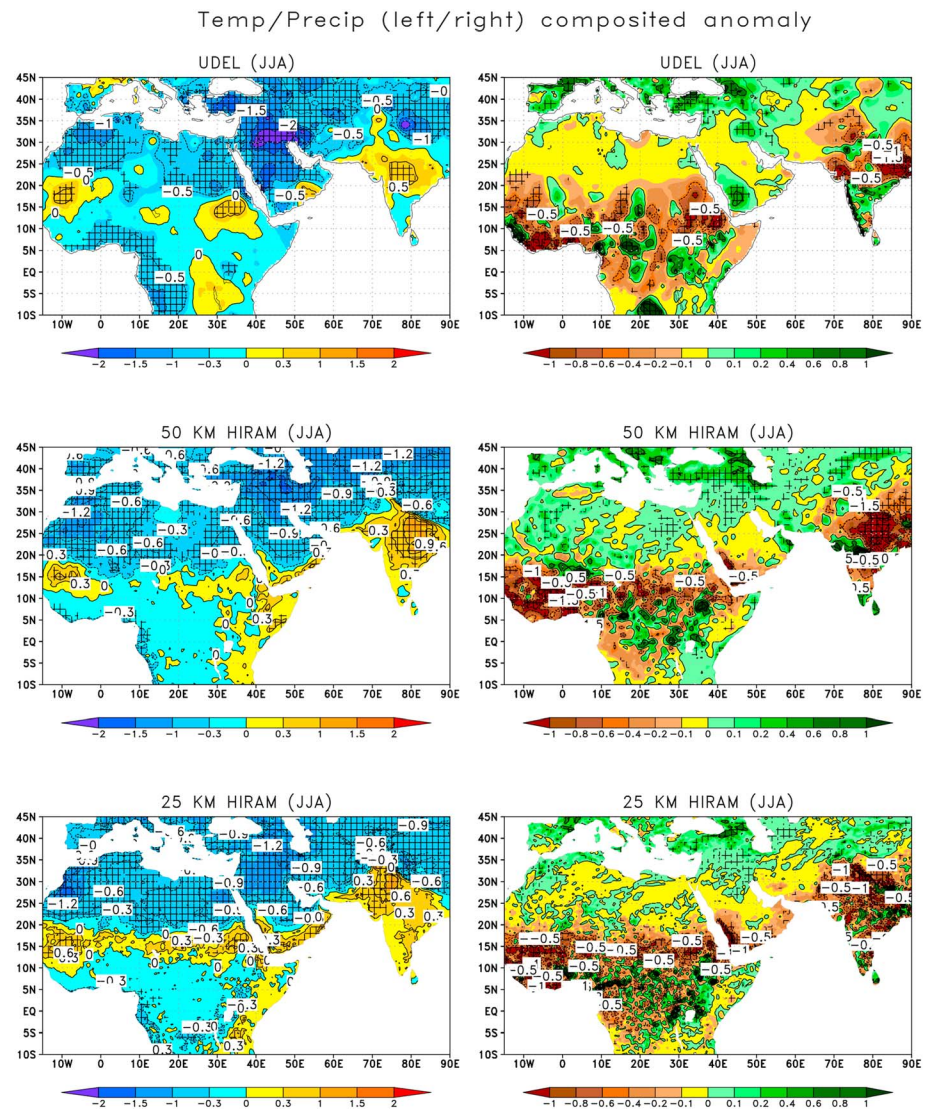


Figure 1. Summer (June–July–August, JJA) surface temperature (K) and precipitation (mm/day) anomalies composited for El Chichón and Pinatubo periods and for 2 years after each eruption. Hatching shows the statistically significant areas with at least 95% confidence level.

changes in temperature and precipitation distribution (Dogar, Stenchikov, et al., 2017; Fischer et al., 2007).

To quantify these effects, we examined simulated spatial patterns of surface air temperature and precipitation fields following El Chichón and Pinatubo eruptions and compared them with UDEL observations (Figure 1). Our analysis reveals that both these events on average cause substantial cooling (warming) and associated increased (decreased) precipitation anomalies over African, Arabian Peninsula, and South Asian regions. We notice that the simulated temperature response is in better agreement with observation at both resolutions. However, model at 25-km resolution shows smoother and consistent (constant) pattern than at 50-km resolution, presumably because HIRAM at 25-km resolution can better simulate regional processes. Both the model and UDEL observation show cooling signal that reaches a maximum value of about -2°C (in the observed response) over the northern part of the selected domain especially over the Arabian region and -0.5°C over the rest of the MEA and South Asian domain except over the summer tropical convective belt of South Asia (Pakistan, India, Nepal, and Bangladesh) and African Sahel belt, where an increased surface air temperature anomaly that peaks at 0.6°C is observed. This increased surface

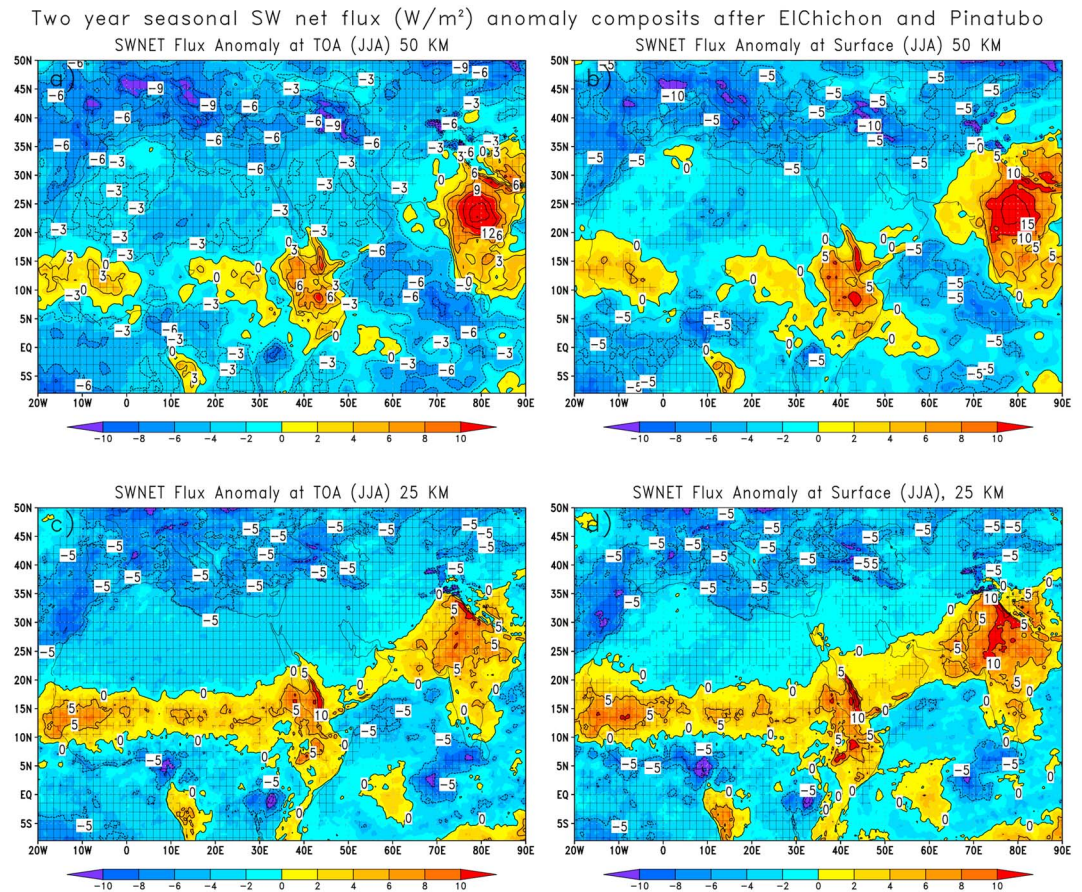


Figure 2. Two-year posteruption seasonally (JJA) averaged solar downward net flux anomalies (W/m^2) at TOA/surface (left/right) from HiRAM at 25-km/50-km (top/bottom) resolution, composited for El Chichón and Pinatubo eruptions. TOA here stands for Top of Atmosphere. Hatching shows the statistically significant areas with at least 95% confidence level.

temperature anomaly is consistent with the increased all-sky shortwave net (SWNET) flux over the tropical region (Sahara/Sahelian belt and south Asian convective regions) in summer (Figure 2). This increased all-sky downward SW net radiation anomaly and the subsequent response of surface temperature are caused by the posteruption circulation changes over the tropics, that is, weakening and southward shift of the updraft branch of local Hadley cell circulation and associated decreased amount of cloud cover (Figure 3).

Reduced precipitation over almost the entire domain with a dipole structure over the tropical region (decrease over Sahel rain belt region and an increasing pattern southward) is seen both in the model simulations and observation (Figure 1, right panel). Precipitation decrease over the tropics (between north of 5°N and south of 20°N) reaches up to -1.5 mm/day both in the model and observation, and these results are consistent with a previous study conducted by Joseph and Zeng (2011), where the authors presented posteruption summer composited response of Agung, El Chichón, and Pinatubo eruptions. These results (i.e., the meridional dipole precipitation pattern seen in Figure 1, over African tropics, especially, over the Sahel rain belt region) are also in agreement with Haywood et al. (2013); however, they considered El Chichón event only. The northern part of the selected domain, especially South and Southeastern Europe, displays a marginally increased precipitation pattern, and this increased precipitation anomaly is consistent with a study conducted by Fischer et al. (2007) that showed similar precipitation pattern in the first summer following large explosive eruptions. The precipitation anomaly pattern produced by HiRAM simulation is in agreement with previously reported observational and climate model results (Dogar, Stenchikov, et al., 2017; Fischer et al., 2007; Iles et al., 2013; Iles & Hegerl, 2014; Joseph & Zeng, 2011; Trenberth & Dai, 2007), implying that our results are robust across models. Trenberth and Dai (2007) also showed decreased precipitation over MEA region, particularly over the tropics; however, they considered the entire year following the

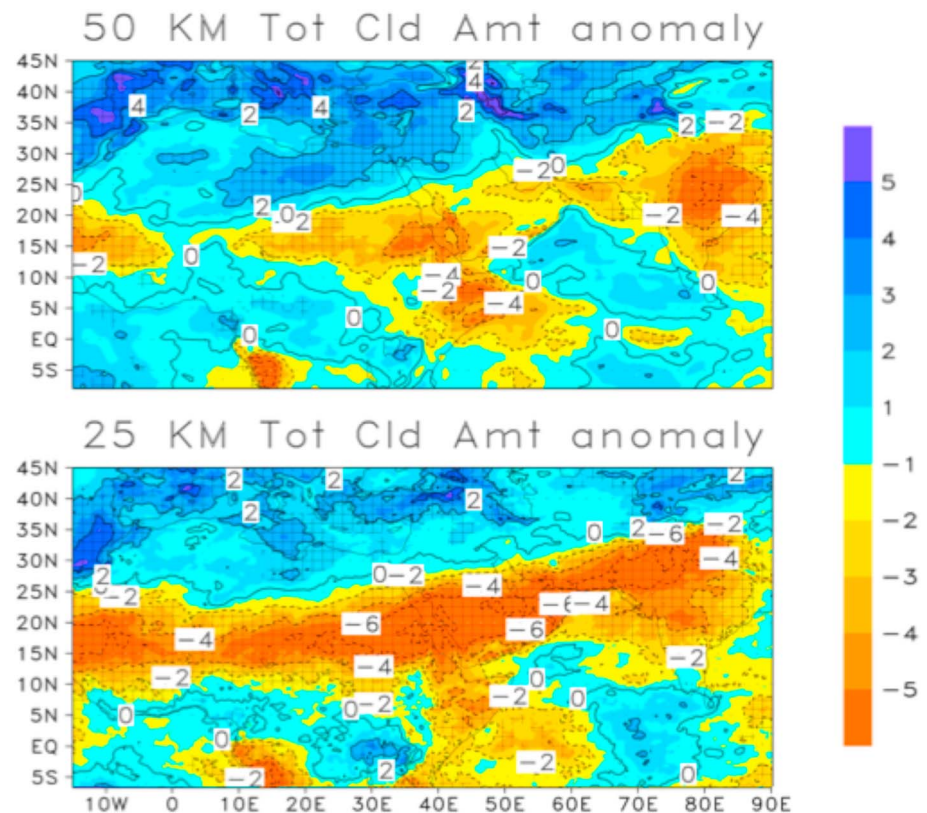


Figure 3. Two-year posteruption seasonally (JJA) averaged total cloud cover anomalies (%) from HIRAM at 50-km/25-km resolution (top/bottom), composited for El Chichón and Pinatubo eruptions. Hatching shows the statistically significant areas with at least 95% confidence level.

Pinatubo eruption, whereas we consider two summers following both the El Chichón and Pinatubo eruptions. Posteruption surface cooling and associated decreased evaporation from the ocean mainly cause this precipitation decrease as a result of decrease of moisture transport toward inland areas. Volcanic-induced summer precipitation response and resultant dipole pattern in the tropics form mainly because of southward shift of ITCZ induced by direct radiative and circulation changes. To further support the hypothesis of posteruption weakening and shift of ITCZ, we look at the seasonal mean and posteruption anomalous responses of wind vectors at 850 hPa using the HIRAM at 50- and 25-km horizontal resolutions (Figure 4). The cross-equatorial reversing monsoonal wind pattern over the rain belt region, 5°N to 20°N, clearly demonstrates posteruption weakening of the Indian and African monsoons (Iles & Hegerl, 2014; Oman et al., 2006) caused by posteruption weakened land-sea thermal gradient and associated weakening and southward shift of the ITCZ. The tropical summer warming and drying anomalies are more pronounced in the model simulations (especially at 25 km) than in observations. This drying in the tropical African Sahel region and the south Asian tropical convective region is caused by the thermal contrast between the Gulf of Guinea and African landmasses (Chang et al., 2008; Dogar, Stenchikov, et al., 2017; Haywood et al., 2013) and Indian Ocean and associated South Asian landmass. Land responds faster to the external forcings than the ocean (because of specific heat capacity difference of land and water), which leads to a weakening of the land-ocean thermal gradient. This leads to decreased moisture transport from ocean to land and suppresses cloud formation. Consequently, the clouds amount and associated water vapor over the tropical convective regions are reduced significantly (Figure 3) that result in precipitation decrease for 2–3 years indicating severe drought conditions (Trenberth & Dai, 2007; Zeng, 2003). Oman et al. (2005) have also reported a decrease in cloud cover after the Katmai eruption of 1912 as a result of the posteruption weakening of Indian and African summer monsoon system. Our results are also consistent with Oman et al. (2006) who showed warming over the tropical belt and reduced water discharge in Niger and Nile Rivers following explosive eruptions. These findings suggest that the climatic responses of NH tropical eruptions, in

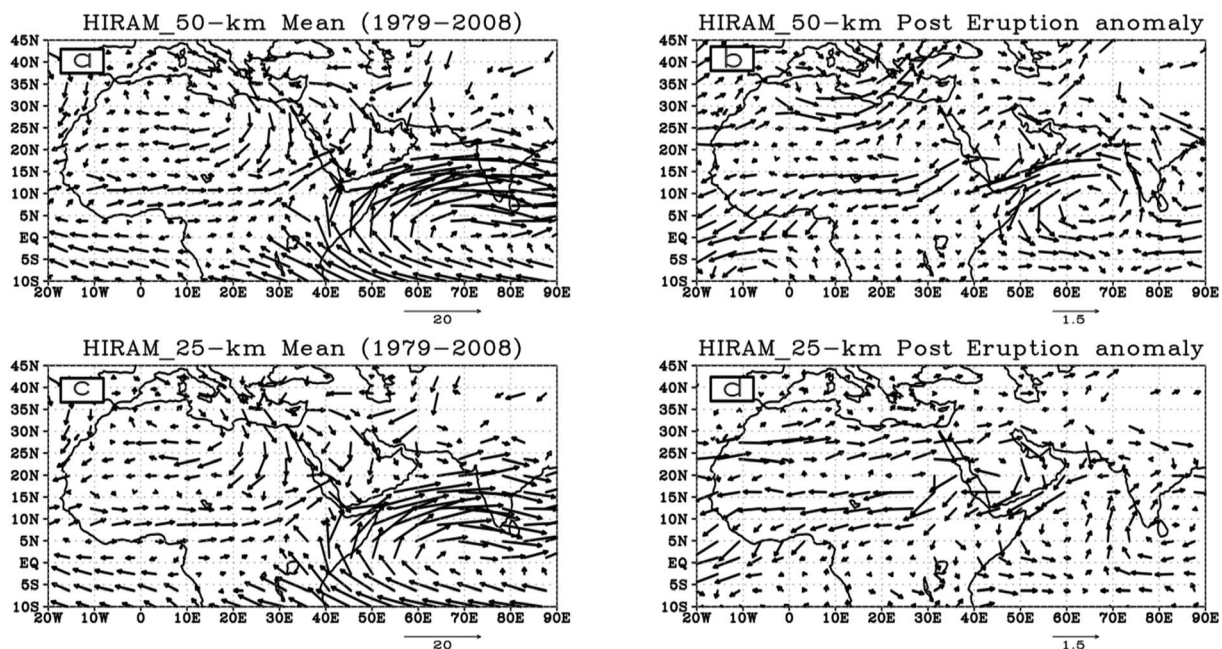


Figure 4. Summer (JJA) mean and posteruption two summer seasons averaged wind vector (m/s) anomaly (composed for El Chichón and Pinatubo eruptions) at 850 hPa from HIRAM at 50-km (a, b) and 25-km (c, d) horizontal resolutions. The mean wind vector plots are computed over the period of 1979–2008 excluding two posteruption summer seasons, and anomaly is shown as a composite response averaged over two summers following both the eruptions.

terms of decreased cloud cover over the NH tropics, weakened summer monsoon, and associated rainfall deficit is roughly comparable to the responses caused by NH high-latitude eruptions.

Climatic responses in the MEA and South Asian region discussed above are produced as a result of volcanic-induced direct radiative and dynamic circulation changes. We also looked at the posteruption composited response of Hadley cell circulation (both at 50- and 25-km resolutions) and noticed that the updraft branch of Hadley cell (i.e., ITCZ) is shifted southward (Figure 5). Moreover, the response and shift of ITCZ shown in 25-km resolution is more compact and more pronounced compared to the model response at 50 km. This Hadley cell circulation response, displayed using mean and anomaly patterns of the zonal mean vertical velocity and zonal mean wind vectors, shows that the HIRAM model at 25-km resolution simulates the circulation responses relatively stronger than 50-km HIRAM model. We noticed that the southward shift in the updraft branch of Hadley cell is consistent with the incoming SW net radiative and cloud amount responses (Figures 2 and 3, respectively). Figure 5 shows that posteruption changes are seen at the surface up to upper tropospheric levels. This suggests that climate forcings (such as volcanism and ENSO) induce hemispheric thermal gradient, especially the land-sea thermal gradient at surface to upper tropospheric levels. These findings are consistent with earlier studies showing the impact of external forcings on the ITCZ and monsoon system through changes in hemispheric thermal contrast on the surface and in the troposphere and associated changes of subtropical jet and Hadley circulation (Chou, 2003; Dogar, 2018; Rastogi et al., 2018; Turner & Annamalai, 2012). To better account for volcanic-induced direct radiative and circulation impacts over MEA and South Asian region both in the model and observations and to better elucidate the impacts of circulation changes, we decompose the effects of ENSO and volcanic aerosols in the following section. From the total responses shown above, we noticed that both model resolutions are picking main features; however, model results at 25 km show more consistent response than at 50-km response, although the quantitative responses are nearly the same. Hence, to avoid recurrences, from now onward, we showed results using the HIRAM model with 25-km resolution only.

3.2. Delineating Volcanic Direct Radiative and ENSO Circulation Effect

Many earlier studies have shown that the El Niño-Southern Oscillation is affected by volcanic impacts (Adams et al., 2003; Emile-Geay et al., 2008; Maher et al., 2015; Mann et al., 2005; Ohba et al., 2013; Pausata et al., 2015; Predybaylo et al., 2017). Both the El Chichón and Pinatubo volcanic events happened

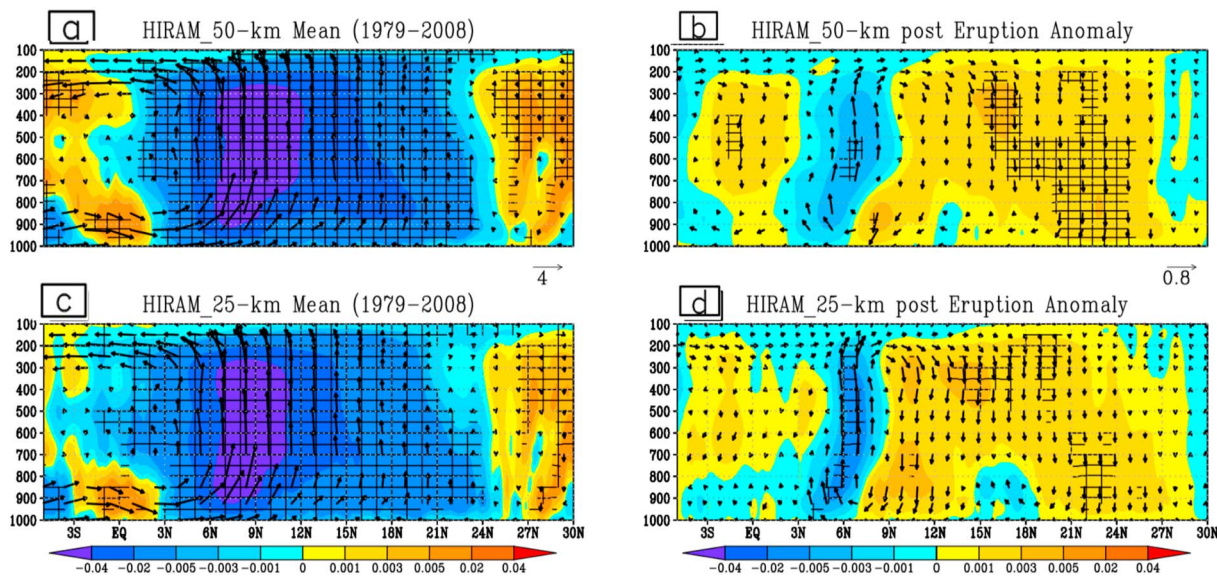


Figure 5. Mean (left panel) and anomaly (right panel) of globally zonal mean omega (vertical velocity in shaded colors; Pa/s) with overlaid globally zonal mean wind vectors (v ; $-100 \times \omega$, m/s; $100 \times \text{Pa/s}$) in the latitude-pressure plane. The mean pattern is shown using (a) HIRAM at 50 km and (c) HIRAM at 25 km, and the posteruption two summer seasons averaged anomaly patterns (composited for El Chichón and Pinatubo period) are shown using (b) HIRAM at 50 km and (d) HIRAM at 25 km. Positive shaded values in color bar represent sinking motion, whereas negative values represent the rising branch of Hadley cell. Hatching shows the areas where the mean and anomaly patterns are significant at 95% confidence.

at the same time when a strong ENSO teleconnection also happened. It has been shown in previous studies that the last three major volcanic eruptions (Agung [1963], El Chichón [1982], and Pinatubo [1991]) coincided with El Niño-Southern Oscillation events (Timmreck, 2012; Trenberth & Dai, 2007).

Previously, a large number of studies have evaluated volcanic radiative impacts over MEA (Wegman et al., 2014; Trenberth & Dai, 2007; Dogar, Stenchikov, et al., 2017; Haywood et al., 2013; Oman et al., 2006) and south Asia (Wegman et al., 2014; Dogar, 2018; Liu et al., 2016; Kravitz et al., 2010; Kravitz & Robock, 2011). They concluded that both the tropical and high-latitude eruptions affect the ITCZ and hence precipitation patterns. Similarly, ENSO also has a larger impact over the Indian Ocean and the Atlantic Ocean through walker circulation such that positive phase of ENSO weakens Indian and African monsoon (Dogar et al., 2018; Dogar, Kucharski, & Azharuddin, 2017; Roxy et al., 2015). The ideal situation would be to see how both the ENSO and volcanic eruptions affect monsoon climate countries, especially the MEA and South Asia region.

A multiple regression analysis (see Appendix A) is carried out to separate the possible trend in the model and observed data and to quantify and delineate direct volcanic radiative and dynamic circulation impacts of ENSO. We considered trend index and ENSO index (based on Nino3.4 region) to estimate and filter out the linear trend in data and to quantify direct volcanic and posteruption impact of ENSO. In order to quantify the volcanic aerosol direct radiative impact, we have analyzed the residual signal in the regression analysis (Randel, 2010; Fujiwara et al., 2015), which is assumed to be composed of volcanic aerosol contribution and some other random variations. The residual method in regression analysis is considered (instead of introducing volcanic index) to estimate volcanic impacts, similar to Randel (2010) and Fujiwara et al. (2015), to avoid losing accuracy in calculations due to multicollinearity between the ENSO and volcanic signals.

3.2.1. ENSO Impact

The El Niño-Southern Oscillation is considered among the leading modes of climate variability (Timmermann et al., 1999; Trenberth et al., 1998; Trenberth & Caron, 2000). Strong atmospheric teleconnections between ENSO phenomenon and associated temperature and precipitation variations at global and regional scale especially in the monsoon belt have been widely discussed (Ashok et al., 2004, 2007; Timmermann et al., 1999; Trenberth et al., 1998; Zhang et al., 2013).

ENSO creates a significant effect on the interannual variation that lasts for a few years. Moreover, recent studies have shown that Northern Hemisphere (NH) summer high-latitude eruptions triggers an El Niño-like

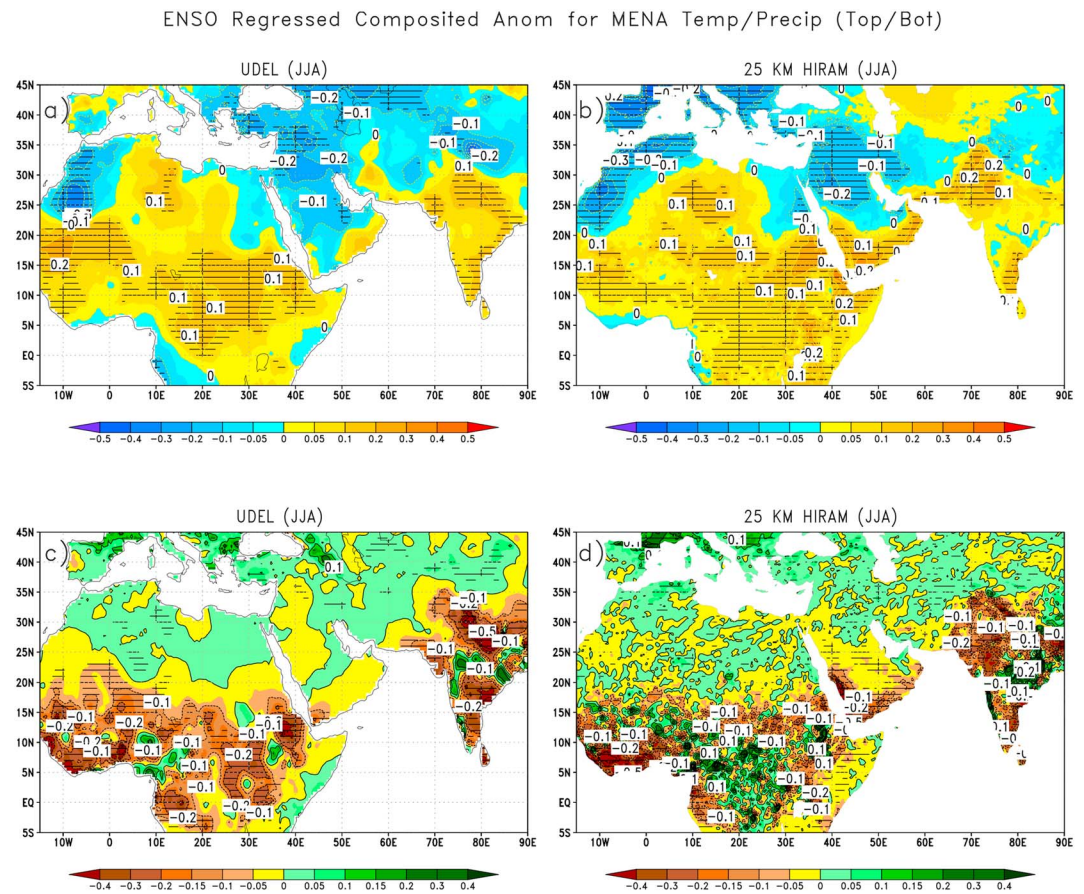


Figure 6. Posterupture two years summer (JJA) averaged ENSO regressed anomaly of temperature/precipitation (top/bottom) from UDEL/HiRAM (left/right) composited for El Chichón and Pinatubo. Hatching shows the statistically significant areas with at least 95% confidence level.

anomaly in the first couple of months that presumably weakens the trade winds along the equator through southward shift of ITCZ in the central and western Pacific, via the ocean-atmospheric Bjerknes feedback (Pausata et al., 2015, 2016). In case of low-latitude tropical eruptions, some studies (both models and proxy records) favor that they trigger El Niño-like anomalies (e.g., Adams et al., 2003; Emile-Geay et al., 2008; Liu et al., 2018; Maher et al., 2015; Mann et al., 2005; Ohba et al., 2013), while others show La Niña-like response (D'Arrigo et al., 2009; McGregor & Timmermann, 2011). The volcano-triggered ENSO in terms of different eruption types and initial ocean conditions has been well discussed in both reconstruction and simulations in recent works (see, e.g., Liu, Xing, et al., 2018). A recent study based on GFDL-CM2.1 coupled model has shown that volcanic eruptions trigger El Niño-like pattern (Predybaylo et al., 2017). These findings clearly demonstrate that for a precise understanding of volcanic impacts, quantification of volcanic-induced ENSO signal is essential.

Figure 6 shows the climatic sensitivity of MEA and South Asian regions to posterupture ENSO events in the summer season, computed using multiple regression analysis on the temperature and precipitation fields from the model at 25-km and UDEL observation. Both the model and observations depict significant warming signal that peaks at 0.2 °C over the tropical belt, except over northern parts of the Arabian Peninsula and southern Europe, where a marginal cooling signal is observed. Both the cooling/warming signals in the summer season are pretty much consistent spatially and quantitatively in model and observations.

We observed a decreased precipitation anomaly (Figure 6, lower panel) particularly over the tropical regions except over some areas covering northwestern Africa and parts of the Eurasian region where a marginally increased anomaly signal is seen. Some parts of central Africa and central India, especially in the model response, also show increased precipitation. Both the magnitude and spatial structure of ENSO-induced

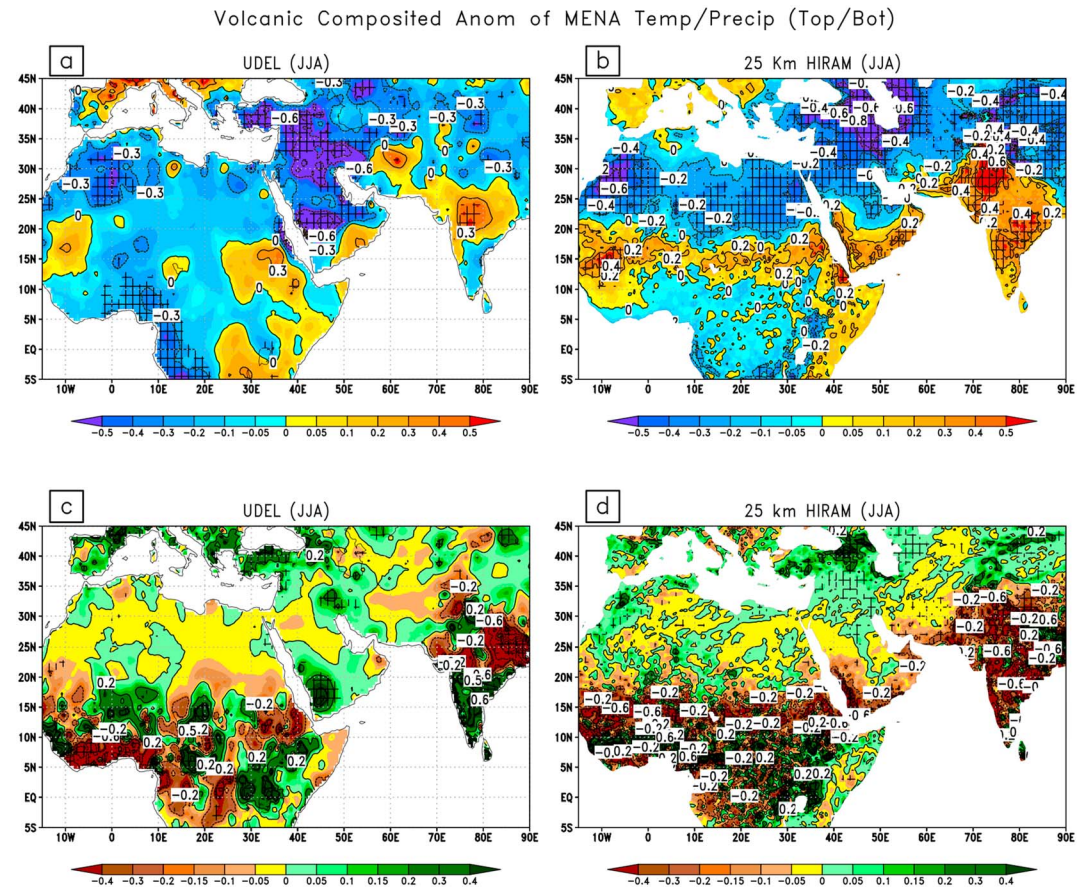


Figure 7. Posteruption two years summer (JJA) averaged volcanic residual anomaly of temperature/precipitation (top/bottom) from UDEL/HiRAM (left/right) composited for El Chichón and Pinatubo. Hatching shows the statistically significant areas with at least 95% confidence level.

precipitation anomalies are in good agreement between the observation and HiRAM simulation. Precipitation anomaly signal is stronger over tropical regions of MEA and South Asia, especially in the areas where significant tropical warming is observed. This ENSO-induced warming and drying over the tropical rain belt region of MEA and South Asia is attributed to ENSO-induced variation in zonal and meridional circulation changes. That in turn produces weak meridional temperature gradient between ocean and inland continents resulting in less amount of cross-equatorial moisture transport from ocean toward inland areas (see, e.g., Shukla, 1975; Ashok et al., 2004, 2007; Roxy et al., 2015; Dogar, Kucharski, & Azharuddin, 2017; Dogar et al., 2018). Precipitation decrease over the tropical region following ENSO events reaches up to -0.5 mm/day both in the model and observations. This regression analysis emphasizes that ENSO plays a significant role to modify MEA and South Asian climate in summer, and it adds a significant portion in the total anomaly pattern. It leads toward warming and drying over the monsoon climate countries that could result in severe droughts as was observed following these eruptions (Dogar, 2018; Dogar, Stenchikov, et al., 2017; Haywood et al., 2013; Oman et al., 2005, 2006). Therefore, a clear perceptive of ENSO signal is obligatory for precise quantification of the volcanic signal. These results emphasize that ENSO is contributing a significant portion of the total anomaly signal shown in Figure 1.

3.2.2. Volcanic Radiative Impact

Figure 7 shows volcanic-induced anomaly pattern of surface air temperature and precipitation in summer season following El Chichón and Pinatubo events, computed as a residual signal obtained by subtracting the trend and ENSO signals from total real signal using multiple regression analysis. We also assessed volcanic direct radiative impact by using volcanic index (calculated using clear-sky net shortwave radiative flux at surface averaged over the selected domain) and introduced it as a predictor in multiple regression analysis; however, it gave similar qualitative responses (not shown) as is calculated using residual approach. The

volcanic residual signal estimated here might contain some contributions (Fujiwara et al., 2015) from other random variations that are not included in the multiple regression; however, these contributions are much smaller compared to volcanic direct radiative and posteruption ENSO impacts, especially in the summer season (Dogar, Stenchikov, et al., 2017). Both the model and observation display cooling and drying anomaly over the entire MEA and South Asian regions except over the tropical belt that displays warming and drying anomaly. The volcanic radiative impact is mainly secondary over the tropical belt as it is under clouds. This volcanic-induced warming signal is caused as a result of posteruption decrease of cloud contents over tropical region and resultant increased all-sky net shortwave radiation flux reaching at the surface. This ITCZ's southward shift and associated radiative and cloud amount responses are consistent, suggesting that volcanism strongly impacts the ITCZ belt. The amplitude of the summer cooling anomaly is more pronounced over Western Sahara, Morocco, and Arabian Peninsula region (Jordan, Syria, Iraq, and Saudi Arabia) both in the model and observations that could be attributed to the volcanic-induced regional changes in clouds contents, planetary albedo and surface sensible and latent heat budget (Atwater, 1970; Crutzen, 2006; Mitchell, 1971). Model results are largely consistent with the observations. Both the model and observation depict significant decrease in precipitation reaching up to -0.6 mm/day (nearly half of the total anomaly) over the tropical regions of South Asia and Africa and increased precipitation at some parts in higher-latitude regions (Southern Europe and Turkey). Some disruption and mixed precipitation pattern over the tropical Sahel region especially in the observation are seen that could be accounted for by scarcity of measurements used to construct observational records; however, the model represents a smoother pattern as model results are averaged over three realizations, and moreover, the model has very fine resolution that could simulate regional processes more effectively. The magnitude of volcanic-induced summer anomaly pattern of surface temperature and precipitation shows that a significant portion of the total anomaly signal is contributed by volcanic direct radiative impact, and the remaining signal in the total anomaly is attributed to ENSO. Here volcanic radiative impact is computed as a residual, and we anticipate that it could have contributions from eruption-induced changes in Indian and African monsoon patterns as they are tightly linked to ITCZ and therefore affect ITCZ (upward branch of local Hadley cell) and hence temperature and precipitation distribution (Anchukaitis et al., 2010; Dogar, Stenchikov, et al., 2017; Haywood et al., 2013; Joseph & Zeng, 2011; Mukherjee et al., 1987; Rodwell & Hoskins, 1996).

4. Summary and Discussion

It is well recognized that monsoon regions experience strong climatic changes following major explosive eruptions. Volcanic-induced climatic impacts over monsoon regions have been discussed in many studies, mostly as direct radiative effect; however, the sensitivity of these regions to forced circulation changes following strong volcanic eruptions has not been explored in detail and therefore remains poorly understood. Moreover, previous studies have discussed the volcanic impacts customarily after excluding ENSO impacts, believing that both the eruption and ENSO events are independent. However, recent studies strongly suggest that ENSO phenomenon could be induced by explosive volcanism, resulting in a need to study combined impact of volcanism and ENSO. This context motivated us to investigate the regional sensitivity of Middle East and Africa (MEA) and South Asian monsoon climate system to strong volcanism considering both direct radiative and forced circulation changes in the summer season.

Therefore, to better quantify posteruption radiative and circulation impacts, a regional climate response to the El Chichón and Pinatubo volcanic eruptions in the MEA and south Asian region is analyzed using global High Resolution Atmospheric Model of GFDL (GFDL-HIRAM), effectively at 50-km (HIRAM-C180) and 25-km (HIRAM-C360) horizontal grid spacing. Two different resolutions of HIRAM are used to see if there is some improvement in the simulation of volcanic impacts with increased model resolution. We used high-resolution GCMs, aiming that due to their fine grid spacing, important processes such as large-scale condensation, land-sea interaction, and topographical forcing are better resolved. This high-resolution modeling system ensures ample grid resolution for regional climate analysis with the ability to better account for global and regional climate responses to volcanic direct radiative and circulation impacts.

We analyzed posteruption changes in solar radiation, surface temperature, cloud amount, and associated precipitation patterns and compared simulated responses with UDEL temperature and precipitation patterns. Multipleregression analysis is used to evaluate the volcanic direct radiative and posteruption

dynamic impacts following El Chichón and Pinatubo eruptions. The multivariate regression analysis just statistically extracted the time series of the signals that are linked with ENSO, and the volcanic impact is obtained as the residual term where the processes (whether it is through radiative, dynamic, or other mechanism) were not considered. We assessed volcanic direct radiative impact by using the volcanic index (based on clear-sky net shortwave radiative flux at surface averaged over the entire domain) and introduced it as a predictor variable in multiple regression analysis; however, it produced a similar qualitative response as was calculated using residual approach. We preferred residual approach to avoid multicollinearity between ENSO and volcanic indices, as both are highly correlated.

Based on observation and high-resolution atmospheric model, this study shows that both the El Chichón and Pinatubo eruptions produce significant changes in atmospheric circulation and affect the climate of MEA and South Asia for subsequent two posteruption summer seasons. Posteruption thermal gradient between land and ocean results in a decreased amount of clouds and increased incoming net shortwave radiation over the tropical convective regions. The pattern of cloud amount (Figure 3), especially low clouds (not shown) and associated changes in precipitation, suggests a southward shift of the NH summer ITCZ following these tropical explosive eruptions. This southward shift of ITCZ in summer indicates that strong NH tropical eruptions cause dryness over Sahel and South Asian convective belt by modulating Indian and African monsoon features and adversely affect the agricultural resources that rely on African and Indian summer monsoon system. Such climatic patterns, if persists longer, may lead to a famine condition that will severely influence the life of the African and South Asian inhabitants.

Our results further emphasize that a significant portion of the total cooling/warming (that could reach from one third to half of the total posteruption anomaly) and associated wetting/drying over MEA and South Asian regions are contributed by posteruption ENSO dynamic changes. These findings suggest that volcanic-induced climate perturbations in the MEA and South Asian convective regions cannot be completely explained by volcanic direct radiative impacts, and therefore, quantification of posteruption circulation impacts is equally important. Our results confirm that the combined effect of volcanism and posteruption circulation changes may lead to severe droughts and famine conditions, especially over monsoon climate regions. We observed that both the forcings (volcanism and positive ENSO phase) produce weakening in the upward branch of Hadley circulation and a reduction in monsoon circulation that result in precipitation deficit over the tropical regions in summer season. It has been seen from the previous studies that volcanic forcing produces a meridional dipole precipitation pattern by weakening and southward shift of ITCZ (Haywood et al., 2013; Dogar et al., 2017). This is also roughly reproduced in our results (both increasing and decreasing precipitation anomalies are seen). However, the precipitation response of ENSO (Figure 6), especially in the observations, only shows precipitation decrease and there is no clear sign of increased precipitation in the observations, suggesting that ENSO (positive phase) causes weakening to the ITCZ and reduction in rainfall over the African and South Asian rain belt regions in summer. Nevertheless, precipitation response of ENSO contribution in the model shows some increased precipitation signal over central Africa and central India, suggesting faint dipole precipitation pattern. We observe that the volcanic direct radiative impact mainly produces this dipole pattern. The spatial pattern of precipitation anomaly (Figure 7), that is, the response of direct volcanism, points toward this dipole pattern. Nevertheless, to get a clear picture of the contribution of direct volcanic and posteruption ENSO toward ITCZ shift, more systematic sensitivity experiments are warranted, which are targeted in the upcoming paper. The weakening and southward shift of the ITCZ is further supported by wind vector anomaly patterns (Figures 4 and 5).

HiRAM model at 50-km/25-km grid resolutions not only reproduces direct radiative impacts of volcanic forcing but also reflects fairly well to the dynamic circulation changes. However, simulated climate patterns at 25 km grid spacing are smoother compared to 50 km, presumably because at a finer resolution, model can simulate circulation-induced regional processes relatively better. The anomalous pattern of SWNET radiation, surface temperature, and cloud distribution over the tropical rain belt region is smoother in the 25-km resolution compared to the HIRAM at 50-km resolution, suggesting that the model at 25-km resolution performs somewhat better than the HIRAM model at 50-km resolution. It is possible because the model at 25-km grid resolution could better resolve the global and regional circulation changes and the local orographic effect than 50-km HIRAM resolution (Chen & Lin, 2011; Dogar, 2018). The posteruption SWNET response (both at the TOA and the surface) and the associated temperature response are mostly consistent between both model resolutions; however, they have a difference in magnitude over the tropical belt,

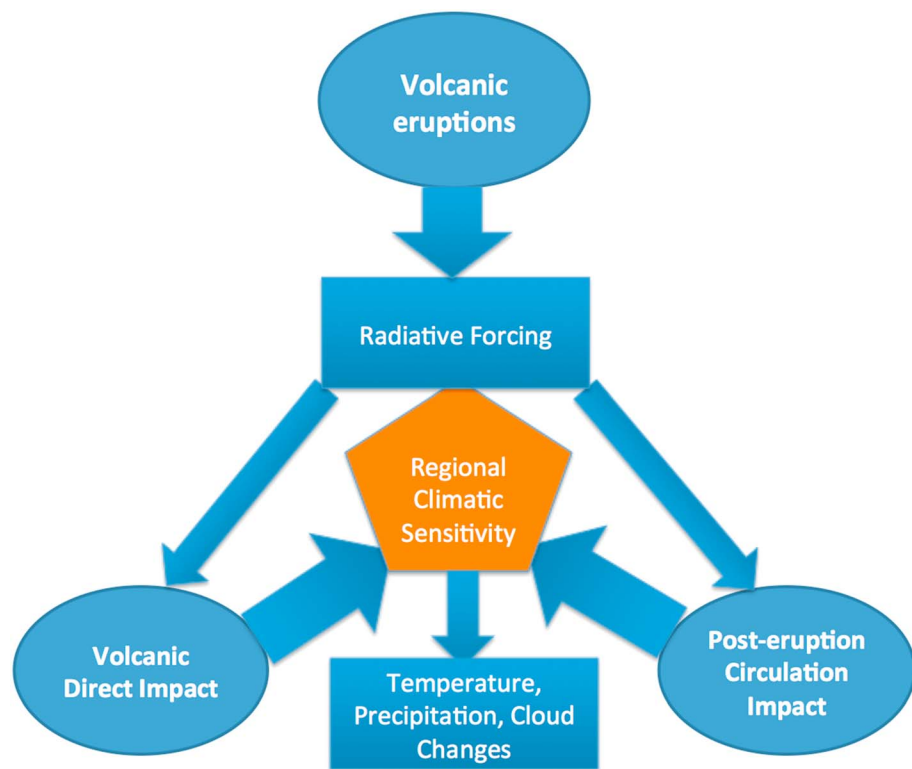


Figure 8. Schematic diagram highlighting the regional climatic impacts of volcanism as a result of the volcanic direct radiative impact and posteruption ENSO impact.

especially over the South Asian tropical regions. The wind vector anomalies (Figure 4) also display marginally varying pattern between both resolutions over south Asian monsoon regions (Pakistan, Nepal, India, and Bangladesh). We also notice discontinuity in downward SWNET radiation and associated surface warming over the Middle Eastern and African tropical regions in 50-km HIRAM simulation compared to 25-km simulation, which shows a constant warming belt. The magnitude of cloud fraction is also marginally different between both model simulations (Figure 3). The consistent anomaly patterns of SWNET radiations, cloud distribution, and surface temperature seen in 25-km HIRAM support that the model at improved resolution reflects relatively better to posteruption climatic changes over the monsoon-fed regions. The lack of consistent warming belt over the tropical African and Middle Eastern region, seen in posteruption UDEL observed temperature pattern (Figure 1), could be accounted for by the scarcity of observational records.

This study shows that MEA and South Asian climate is highly sensitive to the posteruption direct radiative and forced circulation changes; hence, quantification of volcanic radiative and circulation impacts are important for better understanding of the climatic regime of this region. A schematic diagram showing the volcanic direct radiative and posteruption circulation impact (caused by global scale ENSO circulation) of explosive tropical eruption over the Middle East, African, and South Asian regions is shown in Figure 8. In this schematic, we displayed the main components of volcanic radiative forcing that together amplifies the sensitivity of regional climate, which are volcanic direct radiative impacts and posteruption circulation changes (e.g., caused by global scale ENSO circulation). Figure 8 gives a schematic representation of direct volcanic and posteruption ENSO impact over the monsoon-dominated regions. It gives a pictorial view of volcanic-induced radiative perturbations and associated regional climatic responses. It highlights that the volcanic-induced radiative forcing produces volcanic direct impact and posteruption indirect effect through circulation changes. The direct effect is mainly caused by reflection of incoming shortwave radiation by stratospheric volcanic aerosols that results in surface cooling. The reduction of incoming shortwave radiation and resulting cooling over the surface of ocean and land produces land-sea thermal contrast, due to heat capacity difference, which in turn produces a reduction in moisture intrusion from the ocean surface to inland areas, resulting in strong regional temperature and precipitation changes. Moreover, this volcanic-

induced thermal contrast produces strong changes to HC, especially the upward branch of HC that results in reduced precipitation over the tropical regions. The posteruption circulation impact (indirect effect) is mainly produced by the large-scale circulation changes, particularly the ENSO circulation. It is well recognized that the ENSO circulation also strongly affects the Hadley cell and monsoon-fed regions. This study aims to better understand the regional climatic impacts of volcanism and volcano-induced ENSO forcing over the monsoon-fed regions; therefore, we focused on the surface responses rather than the stratospheric responses. We anticipate that the conclusions presented in this study may provide useful guidance to the model intercomparison project on the regional climatic response to volcanic forcing.

5. Conclusions

It is well observed that the monsoon climate countries, especially the African and South Asian monsoon regions, are largely affected by ENSO and volcanic impacts; therefore, the precise understanding of the climatic effects of these forcing factors is required. To better understand these effects, regional climate response to the El Chichón and Pinatubo eruptions in the Middle East and Africa (MEA) and South Asian region is analyzed using a high-resolution atmospheric model effectively at 50- and 25-km spatial resolution. The main findings are summarized below.

1. Volcanic eruptions cause significant warming and drying anomalies over African and South Asian tropical regions in summer. Model and observational analysis shows that the ENSO together with volcanic aerosol direct radiative impact amplifies the posteruption anomalous response, and therefore, resultant warming/drying anomalies are larger than the response of volcanic eruptions direct radiative impact.
2. Both the observations and simulated responses show warming and drying anomalies over MEA and south Asian summer convective belt in the boreal summer season, which is accounted for by posteruption decreased cloud amount associated with posteruption weakening of upward branch of Hadley cell and weakening of Indian and African monsoon systems.
3. The pattern of zonally averaged vertical velocity, cloud amount, and precipitation changes suggests a southward shift of ITCZ in the boreal summer. We find that a significant portion of the posteruption temperature and precipitation anomalies over MEA and South Asia, particularly in the ITCZ convective region, is characterized by posteruption variation in ENSO and ITCZ/monsoon coupled system.
4. Both the forcings (volcanism and El Niño) produce weakening to the ITCZ/monsoon coupled system that result in significant precipitation deficit over the tropical rain belt regions of the Northern Hemisphere. However, the ITCZ shift is predominantly caused by the volcanic direct radiative impact.
5. GFDL-HiRAM at 50- and 25-km grid spacing responds fairly well to volcanic-induced direct and dynamic circulations. However, model's performance at 25-km grid spacing is somewhat improved compared to 50-km resolution.
6. This study emphasizes that MEA and South Asia climatic regime is highly sensitive to the posteruption radiative perturbations. Moreover, we find that global- and regional-scale circulation changes caused by ENSO and Indian/African monsoon circulations are important driving mechanisms, and therefore, their quantification is important for better understanding of the climate variability and change in this region.

Appendix A: Multiple Linear Regression (MLR) Analysis

We used linear trend index and Nino3.4-based ENSO index in MLR to delineate the impact of ENSO circulation and volcanic direct radiative impact. The linear trend index is included to filter out the possible trend in the model and observed data. The volcanic radiative impact is measured in form of residual anomaly (Randel, 2010; Fujiwara et al., 2015) that is computed by subtracting ENSO and trend signals from the total anomalous signal. The predictors (independent variables) are standardized before using in the regression analysis. The regression relation used for the case of two standardized predictors (trend and Nino3.4) is as follows:

$$\text{Response Variable (Precipitation/Temperature)} = \beta_0 + \beta_1 X_{1,i} + \beta_2 X_{2,i}$$

$$\Rightarrow Y_i = \beta_0 + \beta_1 X_{1,i} + \beta_2 X_{2,i} \quad (\text{A1})$$

where Y_i represents to the response (dependent) variable, for example, temperature or precipitation field, and $X_{1,i}$ and $X_{2,i}$ represent to independent variables (predictors), for example, trend index and Nino3.4

index. Subscript i here represents to time index. Here β_0 is known as intercept and β_1 and β_2 are known as regression coefficients (slope coefficients) of trend and ENSO, respectively. Regressed anomaly for ENSO (Nino3.4) is calculated by regressing this particular Nino3.4 index, that is, $X_{2,i}$ on corresponding slope coefficient i.e., β_2 . The regression coefficients are calculated as follows.

$$\text{Using equation (A1)} \quad \bar{Y}_i = \beta_0 + \beta_1 \bar{X}_{1,i} + \beta_2 \bar{X}_{2,i} \quad (\text{A2})$$

$$\text{From equations (A1) and (A2)} \quad Y_i - \bar{Y}_i = \beta_1 (X_{1,i} - \bar{X}_{1,i}) + \beta_2 (X_{2,i} - \bar{X}_{2,i}) \quad (\text{A3})$$

$$\Rightarrow (X_{1,i} - \bar{X}_{1,i}) (Y_i - \bar{Y}_i) = \beta_1 (X_{1,i} - \bar{X}_{1,i}) (X_{1,i} - \bar{X}_{1,i}) + \beta_2 (X_{2,i} - \bar{X}_{2,i}) (X_{1,i} - \bar{X}_{1,i}) \quad (\text{A4})$$

$$\Rightarrow E[(X_{1,i} - \bar{X}_{1,i}) (Y_i - \bar{Y}_i)] = \beta_1 E[(X_{1,i} - \bar{X}_{1,i}) (X_{1,i} - \bar{X}_{1,i})] + \beta_2 E[(X_{2,i} - \bar{X}_{2,i}) (X_{1,i} - \bar{X}_{1,i})] \quad (\text{A5})$$

$$\Rightarrow \text{Cov}(X_{1,i}, Y_i) = \beta_1 \text{Var}(X_{1,i}) + \beta_2 \text{Cov}(X_{2,i}, X_{1,i}) \quad (\text{A6})$$

$$\Rightarrow \beta_1 = \frac{\text{Cov}(X_{1,i}, Y_i)}{\text{Var}(X_{1,i})} - \beta_2 \frac{\text{Cov}(X_{1,i}, X_{2,i})}{\text{Var}(X_{1,i})} \quad (\text{A7})$$

$$\text{Similarly, we get} \quad \beta_2 = \frac{\text{Cov}(X_{2,i}, Y_i)}{\text{Var}(X_{2,i})} - \beta_1 \frac{\text{Cov}(X_{1,i}, X_{2,i})}{\text{Var}(X_{2,i})} \quad (\text{A8})$$

Where E represents the expected value, and Cov/Var is the covariance/variance operator. Last two equations are solved simultaneously for β_1 and β_2 . The residual term is computed as the difference of the observed and predicted response variable, that is, *observed response variable* $- Y_i$.

Acknowledgments

The HiRAM simulation data at both resolutions, that is, HIRAM-C360 and HIRAM-C180, can be accessed from <http://nomads.gfdl.noaa.gov:8080/DataPortal/cmip5.jsp>. The NOAA/OAR/ESRL PSD, Boulder, Colorado, United States provides the UDEL observation data set, through their website at <http://www.esrl.noaa.gov/psd/>. The simulation results and figures are also available from the authors upon request. The authors would like to thank the Japanese Society for the Promotion of Science (JSPS) and Hokkaido University for supporting this research through the JSPS RONPAKU Program. Competing financial interests. The authors declare no competing financial interests.

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