A Review of El Niño Southern Oscillation Linkage to Strong Volcanic Eruptions and Post-Volcanic Winter Warming

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ABSTRACT

Understanding the influence of volcanism on ENSO and associated climatic impacts is of great scientific and social importance. Although many studies on the volcano-ENSO nexus are available, a thorough review of ENSO sensitivity to explosive eruptions is still missing. Therefore, this study aims to provide an in-depth assessment of the ENSO response to volcanism. Most past studies suggest that there is an emerging consensus in models, with the vast majority showing an El Niño–like SST response during the eruption year and a La Niña–like response a few years later. RCP8.5-based climate model projections also suggest strong El Niño conditions and significant monsoonal rainfall reduction following strong tropical volcanism. However, some studies involving climate reconstructions and model simulations still raise concerns about the ENSO-volcano link and suggest a weak ENSO response to volcanism. This happens because ENSO response to volcanism seems very sensitive to reconstruction methods, ENSO preconditioning, eruption timing, position and amplitude. We noticed that some response mechanisms are still unclear; for instance, how the tropical volcanic forcing with nearly uniform radiative cooling projects onto ENSO when coincidental ENSO events are underway. Moreover, there are fewer observational and proxy records for extratropical volcanism impact on ENSO. Nevertheless, model-based studies suggest that Northern (Southern) Hemispheric extratropical eruption may lead to an El Niño (La Niña)–like response. We further noticed that the origin of post-eruption winter warming is still elusive, however, recent findings suggest that the large-scale circulation changes concurrently occurring during volcanism are the potential source of high-latitude winter warming. Existing uncertainties in the simulated ENSO response to volcanism could be improved by considering a synchronized modeling approach with large ensembles.

Key words: Tropical Volcanism, Extratropical Volcanism, El Niño–Southern Oscillation (ENSO), General Circulation Models, Observations, Climate Proxies.

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1. Introduction

The El Niño–Southern Oscillation (ENSO) shapes global climate patterns yet its sensitivity to external forcing remains ambiguous. Modeling studies suggest that ENSO is sensitive to sulfate aerosols associated with explosive volcanism but observational support for this effect remains uncertain. This paper reviews the current state of knowledge of volcanic eruptions and its impacts on ENSO variability, using proxy reconstructions and recent modeling results from state-of-the-art global climate models. The primary focus in this review is to discuss latest progress and consensus on the impacts of strong tropical and extratropical eruptions on ENSO, whose variability has tremendous economic and societal impacts.

It is well known that the large volcanic eruptions produce profound global and regional influences by affecting both the atmosphere and ocean circulation (Robock, 2000, Driscoll et al. 2012; Stenchikov et al. 2006, 2009; Ding et al. 2014; Fujiwara et al. 2015, 2020; Dogar et al. 2017; Swingedouw et al. 2017; Dogar, 2018; Dogar and Sato, 2019; McGregor et al. 2020). Climatic impacts of explosive volcanic eruptions include a temporary disruption of global surface warming due to their strong surface temperature cooling effects (Fyfe et al. 2013; Haywood et al. 2014; Santer et al. 2014; Maher et al. 2015; Medhaug et al. 2017, Monerie et al. 2017). Large explosive eruptions potentially inject immense sulfur-containing gases, ash and sulfur rich aerosols into the lower part of the stratosphere, where they surround the globe through circulation. These volcanic aerosol particles scatter and absorb incoming solar radiation, resulting in a net reduction in surface radiation leading to net surface cooling, and heating of the lower stratosphere (Luther, 1976; Rampino & Self, 1984; Stenchikov et al. 1998; Robock & Mao, 1995; Timmreck, 2012;). Global mean surface temperatures reach maximum cooling within a few months after the eruptions peak in optical depth and get back to normal a couple of years after the event (e.g., Thompson et al. 2009; Timmreck, 2012; Folland et al 2018).

The largest volcanic eruptions also lead to a reduction in ocean heat content and drop in sea level (Church et al. 2005; Pausata et al. 2015; Fasullo et al. 2017; Dogar and Sato, 2020; Ding et al. 2014; Dogar and Shahid, 2020). Volcanic eruptions could also potentially modulate natural climate variability, as they provide suitable conditions in the lower stratosphere leading to the Arctic Oscillation positive phase during the first two boreal winters after eruption (Kodera, 1994; Christiansen, 2008; Marshall et al. 2009; Shindell et al. 2004; Stenchikov et al. 2006). Given that El Niño tends to be associated with a negative phase of the North Atlantic Oscillation (NAO), there is also a possibility that post-eruption ENSO variability influences the global volcanic response through stratospheric pathways (Marshall et al. 2009; Ineson and Scaife, 2009; King et al. 2018).

Recently, several studies have strengthened the case for impacts of volcanic eruptions on the El Niño–Southern Oscillation (e.g., McGregor & Timmermann, 2011; Zanchettin et al. 2012; Predybaylo et al. 2017, 2020; Hermanson et al. 2020; Pausata et al. 2020; Yang et al. 2022) and if

ENSO modulation by volcanic events is strong, it may likely enhance our understanding on the predictability of El Niño/La Niña events after future volcanic eruptions. Given the strong ENSO influence on global and regional climate and its strong societal importance, we therefore review the current evidence associated with the impact of strong volcanism on ENSO.

Analysis of observational Sea Surface Temperature (SST) and surface air temperature suggests that El Niño events overlapped with four large eruptions that occurred in the recent historical period (Figure 1 and Figure 2). MacCracken and Luther (1984) first identified the apparent connection between volcanism and ENSO (i.e., an El Niño type event develops within a few seasons after El Chichón type forcing) using statistical dynamical climate model, which latter was supported by Handler (1984, 1986, 1989). However, the relationship shown in Handler (1984, 1989) was mainly based on serial correlations between both phenomena that appeared in observed SST anomalies composited around volcanic events (Figure 1). A detailed initial review of volcano-El Niño hypothesis, mainly based on statistical correlation methods, could be seen in past studies (e.g., Mass and Portman, 1989; Handler and Andsager, 1994; Adams et al. 2003). Questions about Handler's (1984) results arose due to the methodology used to study statistical robustness, volcanic chronology, and volcanic events timing relative to the onset of ENSO event (e.g., Sear et al. 1987; Nicholls, 1988; Handler 1989; Handler and Andsager, 1994; Self et al. 1997; Robock, 2000; Stevenson et al. 2017). This is obvious in Figure 1a, as both the 1982 El Chichón and 1991 Pinatubo volcanic eruptions happened after the onset of El Niño events in the relevant years, suggesting a coincidental relationship. However, this could also be related to ENSO preconditioning and its linkage to volcanic forcing (Predybaylo et al. 2020; Zhu et al. 2022).

Xing et al. (2020) examined the composite global surface air temperature (SAT) anomalies during the first boreal winter after five 20th Century eruptions in the reanalysis and GISS Surface Temperature (GISTEMP) observations. Both in 20th Century Reanalysis version 2c (20CRv2c; Figure 2a) and observations (GISTEMP; Fig 2b), a pause in post-eruption global cooling during the first boreal winter appeared due to significant El Niño–like warming in the tropics and strong warming in Eurasia, which is consistent with previous finding (Robock and Mao 1992).

Similarly, by using observational and modeling studies, Chai et al. (2020) also studied the apparent ENSO link to 20th Century large tropical eruptions. In observational records of the Agung in 1963, El Chichon in 1982, and Pinatubo in 1991 eruptions, the El Niño peak occurred in the first winter after each eruption (Figure 3). Following aforementioned three tropical eruption events, westerly anomalies over western-to-central equatorial Pacific (WCEP) emerged before the peak of the El Niño phase. However, relying on three cases only, it cannot be concluded that these westerly anomalies are caused by tropical eruptions, as the coincidental occurrence could occur simply due to unrelated internal variability (Self et al. 1997; Robock et al. 1995; Menegoz et al. 2018). However, Chai et al. (2020) took composites of the community earth system model (CESM) large

ensemble (CESM-LE) experiment with 41 ensemble members and using a large ensemble mean to reduce internal variability, reproduced the El Niño response during the second winter following these three eruptions individually (Figure 3). Prior to the peak El Niño phase in the year of the eruption; a significant westerly anomaly from WCEP is modeled for each eruption. El Niño then develops and reaches its peak in the second northern winter. Figure 3 further suggests a weak La Niña–like response in the observations at year (2) and the CESM-LE simulation at year (3), especially for the Agung and El Chichon eruptions. This La Niña–like response largely resembles the results of Maher et al. (2015) who analyzed CMIP5 models and showed a La Niña–like response a couple of years after the large tropical eruption events. These La Niña–like responses have also been suggested by other researchers (e.g., Li et al. 2013; Pausata et al. 2015). Although this transition to La Niña-like responses is argued to be dynamically driven rather than a direct consequence of general post-eruption cooling (Pausata et al. 2016), the underlying mechanism for these rapid eruption-induced El Niño transitions to La Niña needs further investigation.

The current idea encompassing the volcanism influence on ENSO has evolved from the forunner hypothesis suggesting that volcanism has the tendency to modulate the probability and/or intensity of ENSO activity, however, a clear understanding of this relationship is still obscure. Therefore, the rationale behind the present review article is to summarize our understanding of how volcanic eruptions occuring in the tropics and extratropics may influence ENSO forcing using up-to-date literature on climate proxies, and climate model simulations. This summary will include a discussion about how ENSO modulation could occur following strong tropical and extratropical volcanism. The sensitivity of the results to eruption magnitude and timing will also be reviewed keeping in mind ENSO preconditioning at the time of the eruption. In addition, we will also review the mysterious post-volcanic high-latitude winter warming effects on Eurasia and North America. The rest of this review article is organized as follows: Section 2 and 3 present the details of the ENSO and volcanic forcing respectively. Section 4 discusses the volcano influence on ENSO from paleoclimate proxy evidence, while Section 5 outlines volcano influence on ENSO from model-based studies. Key underlying mechanisms suggested so far to understand the influence of volcanic forcing on ENSO are also analyzed and reviewed in Section 5, whereas Section 6 highlights the sensitivity of ENSO and volcanism to ocean circulation. Section 7 reviews in detail the potential role of ENSO preconditioning, eruption seasonality, position and magnitude in the ENSO response mechanism. Post-eruption high-latitude winter warming effects are discussed in Section 8. Summary and concluding remarks on volcano-ENSO linkage are briefly discussed in Section 9 and Section 10.

2. ENSO

El Niño–Southern Oscillation (ENSO) is one among the prominent interannual climate fluctuations on Earth (McPhaden et al., 2006) observed through alternating warm and cold SST

conditions in the tropical Pacific (Trenberth et al. 1998; Timmermann et al. 1999; Yeh et al. 2018) and is considered one of the main driver of ocean and the atmospheric climate variability. ENSO variability has the potential to produce extreme events (e.g., droughts, floods) and variations in cyclone activity through global scale atmospheric teleconnections (Nicholls, 1985; Trenberth et al. 1998; Power et al. 1999; Dogar and Almazroui, 2022). The climatic impacts of ENSO variability and its intensity on global and regional temperature, precipitation, pressure and associated wind have been extensively discussed in several studies (e.g., Timmermann et al. 1999; Ashok et al. 2007; Zhang et al. 2013; Zhang et al. 2015; Dogar et al. 2019). Similarly, the direct radiative impact of volcanism on global and regional climate is also discussed in detail in several studies (Robock, 2000; Haywood et al. 2013; Dogar et al. 2017). However, ENSO linkage to volcanic activity is not explored much and limited research has been conducted in this direction.

In recent studies it has been shown that the volcanic forcing may trigger El Niño–like temperature anomalies in winter and summer seasons following volcanism. For instance, Dogar and Sato (2019) used statistical methods to emphasize that the ENSO has a significantly high correlation with regional surface temperatures in winter and summer, implying that it plays a significant role to modulate regional climate. Several other studies also pointed out that an El Niño event could potentially modify a volcanic signal especially in winter (Robock and Mao, 1995, Timmreck, 2012; Dogar et al. 2017). Typically, an ENSO event peaks during winter period, but its evolution could start a year before its peak and subsequent decay could extend around one to two years after the peak period, hence it has the tendency to interact with a volcanic signal during the summer season as well. For instance, Northern Hemisphere (NH) high-latitude volcanic eruptions force an El Niño along with southward shift of the ITCZ within the following 8–9 months during the summer (Haywood et al. 2013; Pausata et al. 2015, 2016). Moreover, tropical low-latitude explosive eruption events tend to develop El Niño–like anomalies for about one year after the eruption (Adams et al. 2003; Mann et al. 2005; Maher et al. 2015; Ohba et al. 2013; Predybaylo et al. 2017). Since the last three major tropical volcanic eruptions (i.e., Agung in 1963, El Chichón in 1982, and Pinatubo in 1991) overlapped with El Niño episodes (Trenberth and Dai, 2007; Timmreck, 2012); thus, the volcanic impacts could be hampered or masked by ENSO impacts. Hence, to precisely assess the volcanic impacts, the removal of ENSO signals (for instance, by using linear regression or superposed epoch analysis) was suggested in past studies (e.g., Sear et al. 1987; Mass and Portman, 1989; Dogar et al. 2017; Robock and Liu, 1994). However, recent studies suggest that the ENSO signal could be modulated by volcanism and vice versa (through post-volcanic indirect circulation effects), therefore, ENSO and volcanic signals need to be studied in conjunction to each other (Dogar and Sato, 2019). Therefore, in this review paper, we revisited climate proxies and past modeling studies to better understand the volcano-ENSO linkages.

3. Volcanism

Our understanding of the microphysical and chemical processes of volcanic aerosols and their effect on climate is still incomplete largely because of small number of massive stratospheric eruptions occurring in the satellite era. Volcanic eruptions potentially inject a massive amount of sulfur rich gases into the lower part of the stratosphere, where they are oxidized, forming sulfate aerosol plume that disturb the earth radiative balance by scattering the incoming solar shortwave (SW) radiation, and absorption of infrared (IR) radiation (Robock, 2000; Stenchikov et al. 1998; Santer et al. 2014). This disruption of the Earth's energy budget by volcanic forcing can persist for two to three years (Robock, 2000), contingent on the lifespan of stratospheric aerosols and may extend longer due to effects on stratospheric water vapor (Joshi and Shine, 2003; Soden et al. 2002).

Although the volcanic radiative forcing has short life, its large spatial scale and magnitude make it an important driver of climate variability as it strongly interacts with Earth's radiative Energy budget (Timmreck et al. 2009; Timmreck, 2012). Therefore, strong eruptions cause a reduction in the global surface temperature that can remain for several years following these events, resulting in variations in ocean temperature, sea level and circulation changes that can last for decades (Church et al. 2005; Stenchikov et al. 2009; Dogar et al. 2020; Dogar and Stenchikov, 2013). This makes them an important part of the climate system, regardless of their short stratospheric lifetime (Robock, 2000; Timmreck, 2012). It is, however, challenging to untangle the volcanic impact of individual eruptions at regional scales due to multiple coincident climate phenomena, such as the monsoon circulation and other interfering climate variability modes whose regional climate impacts could be much higher compared to global mean variations caused by the eruption (Liu et al. 2022; Dogar et al. 2017; Fischer et al. 2007; Fasullo et al. 2019; Singh et al. 2020; Tejedor et al. 2021; Zuo et al. 2021).

While the recent volcanic events (e.g., El Chichon and Pinatubo) have been well observed (and forcing effects are well replicated in models), the limited observational data for past volcanic eruptions leads to large uncertainties and biases in the aerosol particle size, hemispheric distributions, and radiative forcing estimates (Stenchikov et al. 2004; Santer et al. 2014; Toohey et al. 2011; Raible et al. 2016; Marshall et al. 2021, 2022). The latest climate models with interactive volcanic aerosols have been shown to effectively simulate the aerosol loading, size distribution and associated climate response following the Pinatubo eruption (Mills et al. 2016; Niemeier et al. 2010; Mills et al. 2017). However, very less data exists to constrain other eruptions of different extents, latitudes, and seasonality. Several recent model studies suggested that the eruption latitude, altitude, strength, and season of occurrence, could induce differences in the aerosol evolution, loading (e.g., Toohey et al. 2011; Kravitz & Robock, 2011), and climate responses (Zhuo et al. 2021). The differences in radiative impacts of volcanic eruptions that occurred at different latitudes

(i.e., tropical and extratropical eruptions) are clearly emphasized (Haywood et al. 2013; Pausata et al. 2015; Liu et al. 2018; Zhuo et al. 2021). Aerosols produced from strong tropical eruptions often surround the entire globe, whereas aerosols from mid-to-high-latitude eruptions are confined to the hemisphere of eruption (Oman et al. 2005; Kravitz & Robock, 2011). Even for tropical eruptions, the dispersion depends on the phase of internal variability such as the Quasi-Biennial Oscillation (Trepte et al. 1993; Jones et al. 2016). Simulations also suggest that an eruption similar to Pinatubo occurring in northern winter will cause significantly greater global cumulative aerosol loading than a similar eruption occurring at any other time of the year (e.g., Stevenson et al. 2017; Toohey et al. 2011; Stoffel et al. 2015). Similarly, for the Northern Hemisphere (NH) high-latitude eruptions of similar magnitude, the largest aerosol loading is obtained for eruptions occurring in summer than in winter (Toohey et al. 2011; Kravitz & Robock, 2011). This strongly suggests that aerosol size, distribution, lifetime, and accompanying climatic effects appear to be dependent on the meteorological state, the eruption season, the latitude, and strength of eruption.

Numerous model simulations, observations and hemispheric temperature reconstructions have been used so far to evaluate the climatic impacts of the major volcanic events. However, volcanically induced cooling derived from model simulations is effectively much higher than the cooling visualized in reconstructions (Mann et al. 2012; Büntgen et al. 2014; Stoffel et al. 2015) with some exceptions following El Chichon and Pinatubo tropical eruptions where strong regional cooling is seen in observation compared to high-resolution atmospheric model (HiRAM) simulations (e.g., Dogar et al. 2017). It suggests that either the modeled forcing is unrealistically high or the proxies underestimate cooling (Anchukaitis et al. 2012; Mann et al. 2012; Stoffel et al. 2015; Dee and Steiger, 2022) and/or the model cooling response is overestimated (Chylek et al. 2020; Stoffel et al. 2015; Marshall et al. 2021), perhaps due to a weak response in the Arctic Oscillation and hence a lack of winter warming (Stenchikov et al. 2006; Marshall et al. 2009; Driscoll et al. 2012; Zambri et al. 2017). Alternatively, support for excessive model forcing is indicated by the results of numerous studies showing that there is no general relationship between the extent of forcing and the global mean temperature response (e.g., Timmreck et al. 2009; Bader et al. 2020). This is related with the microphysical processes of volcanic aerosols including its interaction with volcanic ash that effectively limit the impact of strong volcanic eruptions (Zhu et al. 2021). In particular, while considering past eruptions, fixing the concentration and size distribution of aerosols does not give a realistic and accurate simulation of the eruption effects, and therefore, its use can lead to inaccurate estimations of volcanism (Stoffel et al. 2015; Marshall et al. 2021). Santer et al. (2014) and other studies (Dogar and Sato, 2019) suggest that agreement with observations can be improved if the contribution due to internal variability (e.g., ENSO and NAO) is accounted for. Disparities in model responses to volcanism and their inconsistency with observations and proxy-based reconstructions could also be accounted for by the contribution of

volcanic ash and its interaction with Sulfur Dioxide as volcanic input data used in models is missing this contribution (Zhu et al. 2021).

Above discussion strongly suggests that, regardless of having true estimations of observed impacts particularly for recent massive eruptions, effective modeling of the climate responses or impacts (with true magnitude) of past volcanic events remains challenging and demanding work for climate models partly because of the limited accessibility of precise input forcing data required for correct estimation of radiative forcing even before taking into account model errors (Marshall et al. 2021). Therefore, precise information for past and future eruptions about the time of eruption (i.e., eruption season), latitude, particle microphysics, and size distribution is highly needed to test whether models can realistically replicate accurate response magnitudes (e.g., Zhuo et al. 2021; Zhu et al. 2021; Marshall et al. 2021).

4. Assessment of Volcano-ENSO Linkages using Climate Proxy Records

Several climate proxy datasets are available that detail the dates and strength of past historical eruptions (e.g., Sigl et al. 2015; Gao et al. 2008; Crowley et al. 2008). We noticed that these datasets differ in inception of eruption dates (i.e., starting year). This is because the volcanic dates in Sigl et al. (2015) and Gao et al. (2008) datasets correspond to global estimates of volcanic radiative forcing, while for the case of Crowley et al. (2008), volcanic dates correspond to the tropical estimates (averaged over 30°S-30°N) of radiative forcing. It is believed that the volcanic eruptions contribute greatly to climate variability, but quantifying these contributions is limited due to inconsistencies in the timing of volcanic aerosol loading and subsequent cooling signatures. Earlier studies have revealed that ENSO's response and sensitivity to eruptions over the past millennium appears to be significant, while important uncertainties remain (e.g. Raible et al. 2016; Dee et al. 2020; Hernandez et al. 2020; Zhu et al. 2021, 2022). Some studies suggest that a strong El Niño–like SST anomalous pattern occurs during eruption year that could persist for subsequent years, as shown in the observed 350 years (1649-2000) record (Adams et al. 2003). Contrary to this, other studies propose that tropical volcanism may trigger a La Niña–like response, particularly at longer lead times (Anchukaitis et al. 2010; Li et al. 2013; Maher et al. 2015; Pausata et al. 2015). There is also inconsistency among paleo-reconstructions regarding the magnitude representing increased likelihood of an El Niño episode in the years that follows major eruption events (Stevenson et al. 2017). We noticed that various paleoclimate studies are conducted so far to reconstruct ENSO variability of past events and mostly they show varying results. For instance, Dee and Steiger, (2022) tested the volcanism-ENSO linkage in the past 2000 years long records of Paleo Hydrodynamics Data Assimilation (PHYDA) product and noticed a weak tropical Pacific response following large tropical volcanism resembling to El Niño. These results were also not significant (at 95% confidence) when evaluated using superposed epoch analysis (SEA) and self-organizing maps. Significant results emerged when probability density functions were employed, suggesting that

SEA approach (i.e., composite averaging) seems less sensitive to capture an ENSO response in the presence of strong internal variability. Moreover, inconsistencies were noticed in magnitudes and spatial patterns between climate models and PHYDA regarding ENSO-volcano linkage. This study also suggests that current climate models apparently overestimate ENSO response to volcanism. We further noticed that the paleo-reconstructions also disagree on the magnitude of increased likelihood of an El Niño episode during the years that follows major eruptions. Moreover, due to the lack of observational data for comparison, it is impossible to find the best ENSO reconstruction. A careful analysis of these reconstruction studies reveal that the difference in reconstruction methods and input source data resulted in each study producing different ENSO reconstructions and hence different conclusions (Nicholls, 1988; Tierney et al. 2015; Lee et al. 2013; Braganza et al. 2009; Emile-Geay et al. 2013a, 2013b; Dee and Steiger, 2022).

Fadnavis et al. (2021) showed that during 1871-2016 period, 49% (26 out of 53) of the records of moderate to large tropical eruptions were found to represent El Niño conditions within two years after the eruptions that apparently caused droughts over India as they affected Indian monsoon through weakening of Hadley circulation consistent with the earlier findings of Fadnavis et al. (2019) and Khudri et al. (2017). McGregor et al. (2020) used around 17 reconstructions of ENSO variability, and looked for a consistent response (Table 1). The significance of ENSO response in these reconstructions was computed using Monte-Carlo sampling approach. This study found that around 70% (12 out of 17) reconstructions produced a strong El Niño–like response during the eruption year, whilst none produced a La Niña–like response. It also found that in about two years after the event, 47% (8 out of 17) reconstructions produced a significant (above the 95% level) La Niña–like response. This is likely relevant to the dynamics behind the lagged La Niña–like response in the model analysis of Maher et al. (2015). Thus, these results support the idea that strong volcanic eruption may potentially generate warmer SST in the central and eastern equatorial Pacific region, followed by a La Niña–like response (one year later) due to the ENSO oscillatory nature. Using last millennium reanalysis (LMR) and data assimilation framework, Zhu et al (2022) showed no significant ENSO response to volcanism during the eruption years (i.e., year 0 and year +1; Figure 4). This is something that apparently cannot be solved by more examination of our existing paleoclimatic knowledge. Thus, further modeling experimentation and analysis is needed to better understand the contribution of dynamic modulations and proxy-related problems in making variations across reconstructions.

5. Assessment of Volcano-ENSO Linkages Using Modeling Studies

5.1. Tropical Volcanic Eruptions

There are uncertainties in predicting the impact of volcanic eruptions on the occurrence of El Niño Southern Oscillation using models, since the influence of tropical explosive volcanism is not uniformly simulated within models and large ensembles are needed to isolate forced responses from internal variability. Numerical modeling experiments conducted with selected individual models have mimicked the El Niño response (e.g., MacCracken and Luther, 1984; Ohba et al. 2013; Fadnavis et al. 2021). Early experiments conducted using coupled models of intermediate complexity produce a higher likelihood of an El Niño–like condition or the happening of El Niño events after major eruptions, showing agreement with climate proxies and observational estimates (Mann et al. 2005; Emile-Geay et al. 2008). The simplicity of the intermediate complexity coupled model (e.g., Zebiak & Cane, 1987) and the uniform volcanic forcing used in these simple models, warrant that ocean dynamics (i.e., the dynamical thermostat process) is the only process by which the forcing may project on ENSO. Nevertheless, the role of the dynamical thermostat has been argued in several recent studies (e.g., Pokarel and Sikka, 2013; Gregory et al. 2016; Adam et al. 2003 2016; Noh et al. 2017; Fadnavis et al. 2019). Further studies, using coupled and more complex general circulation models (GCMs), suggest several ways of volcanic forcing projection onto ENSO (e.g., McGregor & Timmermann, 2011; Predybaylo et al. 2017, 2020; Pausata et al. 2020; Fadnavis et al. 2021). The outcomes of some of these coupled model studies imply that volcanic forcing may induce an initial cooling in the equatorial Pacific region (Zanchettin et al. 2012; McGregor & Timmermann, 2011). However, this initial cooling apparently being direct radiative response of volcanic radiative forcing, is dynamically different from a La Niña event (e.g., Stevenson et al. 2017). Even with the initial instantaneous cooling response to volcanism, dynamical variables suggested El Niño–like anomalous patterns emerging about a year after the peak of the eruption (e.g., McGregor & Timmermann, 2011). Evaluation of historical coupled GCM simulations performed for Phase 3 and Phase 5 of Coupled Model Intercomparison Project (CMIP) initially proposed that volcanism and ENSO linkage across CMIP models is somehow weak (e.g., Stenchikov et al. 2006; Driscoll et al. 2012; Ding et al. 2014), which is consistent with recent proxy studies (e.g., Dee et al. 2020; Dee and Steiger, 2022). However, numerous modeling studies conducted using CMIP5 models suggest that a strong volcanic eruption induces an El Niño–like mean response in the Pacific Ocean, suggesting an increased likelihood of El Niño events, that persist for about two years after reaching the peak optical depth of the eruption (Figure 5). The El Niño–like anomalous response of the equatorial Pacific in the year following a major tropical volcanic eruption has also been reported in other modeling studies (see, e.g., Ohba et al. 2013; Stevenson et al. 2017; Predybaylo et al. 2017; Maher et al. 2015; Khodri et al. 2017; Fadnavis et al. 2021; Yang et al. 2022). Nevertheless, some recent modeling studies based on CMIP5 (Xing et al. 2020), Paleoclimate Modeling Inter-comparison Project (PMIP) Phase 3, PMIP3 (Chai et al. 2020), and CMIP6 (Liu et al. 2020) failed to generate an El Niño anomalous response in the first post-

eruption winter and long range forecast studies continue to suggest that at least some ENSO events were already set to occur, irrespective of volcanic forcing (Menegoz et al. 2018).

Coupled Climate models may also be employed to study climatic responses to volcanism with varying strength, locations, and the Pacific Ocean pre-eruption initial state to help understand the dynamics of ENSO modulation (Ohba et al. 2013; Lim et al. 2016; Khodri et al. 2017; McGregor & Timmermann, 2011; Stevenson et al. 2017; Predybaylo et al. 2017; Fadnavis et al. 2021). Some studies initially claimed that an eruption of Pinatubo size or larger is needed to increase the probability of a post-volcano El Niño occurring (e.g. Emile-Geay et al. 2008). A similar threshold of magnitude was also recently presented by Iwi et al. (2012) and Lim et al. (2016), whose model results showed that an El Niño–like response to large tropical eruptions occurs only after a threshold of 15 W/m^2 (i.e., about two or three times greater than Pinatubo). El Niño-like post-volcanic conditions are also recently reported following strong tropical eruptions of the size of Tambora 1815 (about a full order of magnitude larger than Pinatubo), which was enhanced for future climate under RCP-8.5 climate scenario because of, enhanced moisture transport (i.e., ocean-land thermal gradient mechanism) and associated higher sensitivity to monsoon system (Yang et al. 2022). However, above results appear to contrast with the CMIP5 multimodel response, which suggests that the relatively smaller eruptions of Pinatubo size could trigger an El Niño–like response after about a year following the eruption peak (Maher et al. 2015; Fadnavis et al. 2021; Khodri et al. 2017). The 2011 Nabro eruption (erupted near the southern Red Sea region) was smaller than Pinatubo, however, it also produced an El Niño-like response that persisted for two years following the eruption that weakened the Indian summer monsoon and caused droughts (Fadnavis et al. 2021). Part of these differences are likely to be associated with differing model background states and biases, but may also be associated with experimental design (e.g., volcanic events ensemble members used in the composite). Consideration of water vapor feedback in the model during the simulation of eruption events could also play important role to account for such differences (Soden et al. 2002). The initial state (i.e., ocean preconditioning) of the Pacific has also proved to be very important (Predybaylo et al. 2017, 2020; Khodri et al. 2017). The dependence of ENSO's response to Pacific Ocean preconditioning for a Pinatubo-size eruption has been investigated by Predybaylo et al. (2017) using GFDL-CM2.1 coupled model, which reported that relative to an unperturbed simulation, an El Niño–like statistically significant warming appears for all ocean preconditioning states, except for a La Niña initial state introduced in the Pacific. A weaker El Niño condition happens following an El Niño initial state in the equatorial eastern Pacific (EP) compared to a central Pacific (CP) initial state. This suggests that initial states associated to different ENSO flavors (i.e., CP or EP ENSO) are also important as their global and regional impacts especially on the Hadley and walker circulations and associated impacts on monsoon system is largely different (Dogar et al. 2019; Taschetto et al., 2020; Ma et al., 2022). Predybaylo et

al. (2017) and Khodri et al. 2017 further suggested that Pinatubo-size volcanic events cause an El Niño–like warming pattern under all projected scenarios that tend to lengthen El Niño events, shorten La Niña events, and produce anomalous warming signal in the tropical central Pacific Ocean during neutral preconditioning. Predybaylo et al. (2017) also examined the effect of the season of the eruption, and reported a stronger El Niño–like response for eruptions occurring in the boreal summer compared to spring and winter eruptions. These findings suggest that more research is warranted to systematically disentangle the discrepancy between model results attributable to model differences and/or the experimental methods.

Numerous dynamical mechanisms have been identified in CGCM based idealized studies of volcanic effects to elucidate how the zonally symmetric volcanic forcing can interact on ENSO mode. In all cases, it is assumed that the Pacific basin Bjerknes feedback has been initiated (Bjerknes, 1969), following the initial projection on the ENSO mode, which helps to intensify the initial SST anomaly. The El Niño induced by the tropical volcanism in these models is related to several suggested mechanisms: the oceanic dynamic thermostat mechanism (Predybaylo et al. 2017; Ohba et al. 2013), the equaterward movement of the Intertropical Convergence Zone caused by decreased evaporation on cloudless subtropical regions (Haywood et al. 2013; Lim et al. 2016), the western land-ocean temperature anomaly induced by thermal contrast (Predybaylo et al. 2017), and the westerly response to the suppressed West African monsoon (WAM) and warm pool precipitation (Khodri et al. 2017; Chai et al. 2020). Two other factors may also influence the simulation of El Niño–like responses after tropical volcanic eruptions: the initial condition of the ocean (e.g. Menegoz et al. 2018) and the strength of the eruption. It is difficult to replicate an El Niño when the initial ocean condition is already in the El Niño peak phase before the eruption (Liu et al. 2018). Furthermore, the volcanic eruption must be strong enough to stimulate an El Niño (Emile-Geay et al. 2008; Lim et al. 2016). The details of these mechanisms that allow ENSO modulation by volcanic forcing (i.e., subtropical wind stress curl, dynamical thermostat, and land temperature changes) can be seen in McGregor et al. (2020) and Zhu et al. (2021).

Liu et al. (2018) performed a millennium volcanic sensitivity experiment using CESM model version 1 (CESM1) forced with volcanic reconstructions of Gao et al. (2008), for 1500 years (i.e., 501 to 2000 AD), to identify the ENSO response to tropical and extratropical eruptions. CESM has been used effectively to investigate volcano-ENSO linkages (Stevenson et al. 2017; Otto-Bliesner et al. 2016). A long control simulation (2000 years) was performed as a reference where all external forcings were fixed at the values of year 1850. Using this long control run, a forced volcanic simulation is carried out for the period of 501 to 2000 AD, keeping the external forcing at the same level as used in the control run except that the reconstruction of volcanic aerosols spanning 501 to 2000 AD was added as a variable driving force (Gao et al. 2008). During the simulated 1500 years, there were 25 tropical, 16 NH, and 13 SH volcanoes. In these sensitivity

experiments, it is noticed that, compared to the internal El Niño in the control run (Figure 6), the shift from El Niño to La Niña is quicker for the tropical volcanic-induced El Niño. The negative NINO3 index emerges early in May for this forced El Niño mode, which only appears in July for the internal mode in the control run. The La Niña following the El Niño for the volcanic-forced mode is also stronger than the purely internal ENSO. The easterly anomalous wind over the western Pacific appears in May after the El Niño for the internal mode, while it appears early in January and is stronger for the eruption forced mode. Since the volcanic forcing could be weak during this El Niño-La Niña transition time, which is the second year after the eruptions, this quick transition after the tropical volcanic-induced El Niño is a dynamically driven, oscillatory response to the preceding El Niño. These results resemble the results of Maher et al. (2015) who analyzed CMIP5 based models and showed a La Niña–like response couple years after the large tropical eruptions.

5.2. Extratropical Volcanic Eruptions

Much modeling work has been done on the impacts of tropical volcanism, especially their role in reducing monsoonal precipitation due to their strong impact on the ascending branch of Hadley Cell and associated equatorward shifting of the Intertropical Convergence Zone, as well as strong linkage to ENSO dynamics (Mass and Portman 1989; McCracken and Luther, 1984; Joseph and Zeng, 2011; Haywood et al. 2013; Dogar et al. 2017; Dogar and Sato 2019; Fadnavis et al. 2021). However, despite the strong sensitivity of ENSO variability to eruptions, very less model studies are conducted so far to examine the impacts of extratropical eruptions occurring in the Northern and Southern Hemispheres (i.e., NH and SH) (Stevenson et al. 2016, 2017; Liu et al. 2018; Zuo et al. 2018; Pausata et al. 2015, 2016). Extratropical volcanic eruptions are less studied than tropical eruptions, since their radiative forcings were considered hemispheric only, as aerosols were confined to the eruption hemisphere rather than the global. Their hemispheric TOA radiative forcing can shift the Intertropical Convergence Zone (ITCZ) towards the warmer hemisphere (Haywood et al. 2013). This is consistent with earlier studies that have highlighted the potential regional impact of large extratropical eruptions on the amplitude of the Asian monsoons (Oman et al. 2005; Liu et al. 2022) and rainfall in Africa (Oman et al. 2006, Haywood et al 2013). Recent studies, however, have shown the possible global impacts of extratropical volcanism through their impacts on ENSO and/or oceanic circulation (e.g., Pausata et al. 2015, 2016; Stevenson et al. 2016; Liu et al. 2018; Zuo et al. 2018). Since, ocean integrates the volcanic signal and responds on a wide range of time scales (Stenchikov et al. 2009; Pausata et al. 2015; Dogar et al. 2020), therefore, the modulation of ocean circulation by extratropical eruptions allows their effects to last for decades.

For extratropical NH eruptions, models simulate a trend towards enhanced El Niño occurrence in the boreal winter after the eruption but differ on whether El Niño–like or La Niña–like states are expected in the second winter (Pausata et al. 2015; Zuo et al. 2018; Stevenson et al.

2016). An inclination towards a La Niña–like response was identified one year after an extratropical SH eruption (Stevenson et al. 2016), suggesting a rebound of El Niño–like conditions, as La Niña conditions normally follow El Niño states (Ohba & Ueda, 2009; Kessler, 2002; Okumura & Deser, 2010). Additional modeling studies and research is needed to verify the proposed dynamic processes and to verify whether such influences of the initial conditions are sufficient to explain the completeness of this response. In the CESM model, the response to SH eruptions appear almost opposite to the response to NH eruptions during the year of eruption. Which is, the SH eruption events cause a northward ITCZ shift together with a strong initial cooling that peaks in the post-eruption boreal winter (Haywood et al. 2013; McGregor et al. 2020). However, the findings of Stevenson et al. (2016) suggest that this response is unlikely to have dynamics consistent with the La Niña episode based on the analysis of the complete spatial pattern of SST anomalies (Stevenson et al. 2016). A rebound to neutral ENSO conditions ensues, which roughly last for the next one year, during which further cooling occurs in the tropical Pacific.

The millennium volcanic sensitivity study by Liu et al. (2018) showed that after the NH eruptions (Figure 7a), the westerly wind anomalies are excited via the Bjerknes feedback to the south of the equator in the first northern winter over the Pacific, and warm SSTs initiate to develop from the eastern Pacific after the northern spring related with westerly wind anomalies. The warm SSTs also initiate to develop in the Eastern Pacific related with the equatorial westerly wind anomalies since the first northern winter after the tropical eruptions (Figure 7b). After SH eruptions, anticyclonic wind anomalies dominate in the Southeast Pacific (Figure 7c) associated with cold sea surface temperature anomalies. It has been shown that compared to westerly wind (and associated surface current) anomalies and their related descending in the central to eastern Pacific, one year after the NH or the tropical eruptions, the easterly wind (and surface current) anomalies and the associated ascending dominate the eastern Pacific one year after the SH eruptions (Figure 8). Thus, this ascending wind, via the Bjerknes feedback (Bjerknes, 1969), inhibits warm SST anomalies to develop in the eastern Pacific.

One major mechanism has been identified that potentially contributes as an instant ENSO response to volcanic events occurring in extratropics, that lasts for about one year, is the shift of the ITCZ. Extratropical volcanic eruption events are characterized by the spread of sulfate aerosol, limited to the hemisphere in which the volcanic eruption occurs. It is commonly known that asymmetric interhemispheric forcing drives the ITCZ away from the hemisphere being cooled by volcanism (Kang et al. 2008; Dogar et al. 2017; Haywood et al. 2013; Schneider et al. 2014). This has been shown in coupled model studies of extratropical eruptions, for instance, simulations of the 1783 Laki eruption in Iceland (Pausata et al. 2015) and entire millennium simulations of extratropical eruptions (Stevenson et al. 2017; Colose et al. 2016). The migration of the ITCZ towards the

equator, in response to a NH eruption, tends to favor the commencing of El Niño events (Pausata et al. 2015; Pausata et al. 2020) although more work is needed to accurately estimate the change in occurrence frequency. Since surface easterly winds are weakest in the immediate vicinity of the ITCZ, this migration to the equator implies a weakening of easterly winds along the equator in the central and eastern equatorial Pacific Ocean. Through the Bjerknes feedback mechanism (Bjerknes, 1969), this weakening of the trade winds result in a decrease in the temperature contrast between east and west in the tropical Pacific, that favors the development of an El Niño–like anomaly. These El Niño–like anomalies could also be affected by the ocean preconditioning (see section 5 for details), that is, pre-existing or background ENSO state: a stronger El Niño–like response develops when the preexisting ocean state is La Niña rather than El Niño (Pausata et al. 2016).

The ITCZ's potential role in inciting ENSO response in the first winter following the extratropical NH eruptions has also been proposed by Stevenson et al. (2016), who show the migration of the ITCZ to the equator after the eruption and subsequent development of El Niño-like conditions. In other earlier studies that examined the impacts of extratropical volcanic forcing on climate (Highwood & Stevenson, 2003; Haywood et al., 2013; Oman et al. 2005, 2006), an analysis of the ENSO response was not feasible due to the lacking of a fully coupled atmosphere-ocean model and the consequent failure to recognize coupled feedbacks. However, by using the coupled model simulations (fully coupled or coupled with a mixed oceanic layer), Zeng (2003), Oman et al. (2005, 2006), and Haywood et al. (2013) showed a suppressing of the Asian and/or African monsoon after the NH eruptions, suggesting a displacement of the ITCZ towards south that provides suitable conditions for the development of El Niño. The study by Zeng (2003), Dogar et al. (2019) further emphasize that the shift of ITCZ and subsequent weakening of monsoon is caused due to El Niño–like SST conditions, which could be related or unrelated to volcanism. This suggests that the ITCZ response to individual forcing (i.e., ENSO or volcanism) or their concurrent ENSO-volcano effect requires specifically designed coupled model sensitivity experiments for better understanding of volcano-ENSO-ITCZ linkage.

6. Volcano-ENSO Linkage and AMOC Role

The intense radiative cooling caused by large tropical volcanic eruptions and allied changes in atmospheric circulation result in colder, saltier and therefore denser upper ocean conditions over convective regions, causing modifications to the oceanic thermohaline circulation (e.g., Otterå et al. 2010; Stenchikov et al. 2009; Raible et al. 2016; Dogar et al. 2020). This lets the cold signal to enter into the deep ocean and to substantially affect the global ocean temperature, sea level and heat content for several decades or even longer (Church et al. 2005; Delworth et al. 2005; Gleckler et al. 2006; Fasullo et al. 2016), thereby protracting the recovery of the climate system from volcanic perturbations. A statistically significant Atlantic meridional overturning circulation (AMOC)

response after strong tropical volcanic eruption of Krakatau 1883 that persisted for several decades with associated northward enhancement in heat transport was reported in a study conducted using Met Office Unified Coupled Model, HadCM3 (Iwi et al. 2012). Similar to tropical volcanism, AMOC responds significantly to NH extratropical eruptions as well, predominantly due to a strong post-eruption ocean cooling that could last for few decades (e.g., Pausata et al. 2015). Numerous studies (both modeling and observational) proposed that AMOC forced changes could modulate the amplitude of ENSO (e.g., Dong & Sutton, 2002; Zhang & Delworth, 2005; Sutton et al. 2007; Timmermann et al. 2007; Pausata et al. 2015; Levine et al. 2017, 2018; Otto-Bliesner et al. 2016; Orihuela et al. 2022). Using a global climate model, Orihuela et al. (2022) showed that forced AMOC changes (i.e., slowdown or collapse under anthropogenic forcing) accelerates the Pacific trade winds and Walker circulation that results in enhanced subsidence and cooling over the east Pacific leading to a La Nina-like condition. The reverse is true for volcanic-induced changes in AMOC (i.e., strengthening under volcanism) that would result in warming over east Pacific that leading to an El Niño-like condition. This relationship is believed to be essentially due to large-scale changes in atmospheric circulation caused by AMOC-induced tropical Atlantic SST gradients, modulating the tropical Pacific, and ENSO (Ruprich-Robert et al. 2017; Polo et al. 2014; Dong et al. 2006; Orihuela et al. 2022). In addition, on a multi-decade scale, thermocline signals related with AMOC strength can also be transferred from the North Atlantic to the tropical Pacific via ocean waves (Timmermann et al. 2005). These modeled oceanic inter-basin relationships denoting that AMOC strong variability results in some variability in the ENSO could be physically reasonable (Atwood, 2015; Timmermann et al. 2007; Ding et al. 2014). However, there are limited observational data to support this oceanic inter-basin ENSO modulation (Atwood, 2015). With regard to extratropical eruptions, Pausata et al. (2015) examined the ENSO modulation following a volcanic event under modern conditions, and indicated that ENSO variance increases with an increase in AMOC and vice versa. The increased variability of ENSO during periods of strong AMOC is believed to be related to the flattening and shallowing of the thermocline in the equatorial Pacific, which enhances the Bjerknes feedback (Russell & Gnanadesikan, 2014; Pausata et al. 2015). More research is needed to investigate the relationship between ENSO variability and AMOC after volcanic eruptions to better quantify long-term climate impacts beyond the lifespan of injected stratospheric aerosols.

7. Role of Ocean Preconditioning, Eruption Location, Seasonality, and Magnitude.

Two mechanisms, land-ocean temperature contrast (LOTC) and the oceanic dynamic thermostat (ODT) are largely proposed to explain volcano-ENSO linkage predominantly for low latitude tropical eruptions (e.g., Pokarel and Sikka, 2013; Gregory et al. 2016; Adam et al. 2003 2016; Noh et al. 2017; Fadnavis et al. 2019; 2021). Both these mechanisms can activate westerly wind anomalies that consequently lead to El Niño-like SST response following strong volcanic

event. The LOTC is based on the heat capacity difference of the land and the ocean; the volcanic-induced temperature contrast between the western Pacific Ocean (WP) and the maritime continent is thought to weaken the trade winds. The ODT relies on the ability of ocean to moderate the SST response to radiative forcing more efficiently in the equatorial region of the eastern Pacific (EP), leading to temperature contrasts between the WP and the EP. Since the ODT is connected with the force of upwelling of equatorial ocean, its strength is closely related to preconditioning of ENSO (i.e., initial state) and, therefore, could also be the cause for divergent strength of the El Niño response following volcanic eruptions.

A study using the CESM climate model indicated another mechanism attributing to a stronger El Niño-like response following the tropical volcanism, associated with post-volcanic El Niño excitation via wind stress curl. This El Niño excitation appears due to post-eruption increased equatorial pacific surface cooling and associated increased heat advection (Stevenson et al. 2017). Khodri et al. (2017) analyzed the CMIP5 simulations along with idealized experiments conducted using the Institute Pierre Simone Laplace coupled climate model (with and without volcano) to understand the key mechanisms of ENSO-volcano linkage. This study linked an El Niño-like response to a volcanic-induced abrupt African continent, which lessened the West-African monsoon and produced westerly wind anomalies in the Western Pacific (Khodri et al. 2017; Fadnavis et al. 2021). A study based on the Norwegian Earth System Model (NorESM) examined the ENSO response to asymmetrically distributed volcanic plume after the tropical volcanic eruptions (Pausata et al. 2016; Pausata et al. 2020). It emphasizes that the leading response mechanisms are related to extratropical circulation changes including shift of the Pacific jet and the changes in the cyclonic surface pressure anomalies in the Pacific mid-latitude region, while the shift of the ITCZ has a lesser role. Nevertheless, for high-latitude eruptions, it has been suggested that an explosive volcanic eruption occurring in the Northern Hemisphere (NH) shift the ITCZ equatorward and thus produce an El Niño-like response (Pausata et al. 2016). However, the variations between ENSO responses to massive volcanism and underlying mechanisms reported in these studies could stem from the inadequate sampling for temporal composites and ensembles. Hence, while investigating the ENSO response to volcanism, the sampling paradigm should essentially account for the following aspects:

a. An ENSO onset (or ENSO preconditioning) that is connected with a set of atmospheric and oceanic conditions before the eruption (Predybaylo et al. 2017, 2020; Pausata et al. 2016; Marshall et al. 2022). These initial conditions are known as Neutral, El Niño, or La Niña starts (i.e., onsets), and in the nonexistence of external forcing, lead to corresponding neutral “normal”, negative, or positive ENSO years. The response of tropical Pacific relies strongly on ocean preconditioning irrespective of eruption type (i.e., high-latitude or low-latitude). For instance, Normal or El Niño

inceptions are more likely to be interfered by low-latitude eruptions than a La Niña onset (Predybaylo et al. 2017, 2020; Ohba et al. 2013). Moreover, CP-type El Niño onsets may respond more intensely than EP-type El Niño onsets (Predybaylo et al. 2017). For instance, global and regional impacts of different ENSOs (e.g., CP and EP-type) especially on the Hadley and Walker circulations and associated impacts on monsoon system are largely different (Dogar et al. 2019; Taschetto et al., 2020; Ma et al., 2022).

b. Timing of volcanic eruption related to the seasonal cycle or ENSO type (Stevenson et al. 2017; Predybaylo et al. 2017; 2020) that may mask strong sensitivity of the ENSO response. Modeling studies show evidences that ENSO type and its response to volcanism is sensitive to the timing and seasonality of volcanic forcing. It is further found that the ENSO response is more robust in summer than in winter (Predybaylo et al. 2017; 2020; Wittenberg et al. 2014), which could be explained by the widely known boreal spring (Feb-May) predictability barrier of ENSO event (McPhaden, 2003; Lai et al. 2018; Ren et al. 2018). This ENSO spring barrier suggests that the ENSO prediction skill is significantly reduced during the boreal spring, because of the tendency of the ENSO episode to shift towards El Niño and La Niña phases decay after their usual winter peak. It is noticed that the coupled climate models face problems in predicting boreal winter tropical Pacific SST when forecasts start in boreal spring (Lai et al. 2018; Zheng et al. 2010). Since volcanic eruptions can occur at any time of the year (Mason, 2004), it is therefore important to separately examine the impacts of volcanic eruptions occurring at different times.

c. Magnitude of volcanic activity that is responsible for ENSO response strength. The stronger the volcanic eruption, the more significant (or more likely) the ENSO response may be (Predybaylo et al. 2017; 2020). For example, the Tambora eruption (three times larger than the Pinatubo), would cool the surface of the EP more within the first year, and then induce a warmer El Niño in the second year than a Pinatubo-sized eruption (Emile-Geay, 2008; Ohba et al. 2013; Stevenson et al. 2017; Predybaylo et al. 2017; McGregor et al. 2011; Li et al. 2013).

d. Location of the volcanic eruption, which is responsible for the aerosol plume distribution and lifetime. Though volcanic aerosols are normally globally distributed for most low-latitude eruptions, they may sometimes be trapped in one hemisphere (Pausata et al. 2020), and for high-latitude explosive eruptions are hemispherically distributed (Oman et al. 2005; Schneider et al. 2009; Kravitz and Robock, 2011; Pausata et al. 2020). All these eruption types can cause a significant ENSO response (Liu et al. 2018). However, the sensitivity of ENSO response is less pronounced for high-latitude eruptions than for low-latitude eruption events due to relatively shorter

aerosol lifespan and varying interfering response mechanisms (Pausata et al. 2015, 2016; Sun et al. 2019; Colose et al. 2016; Stevenson et al. 2016).

8. Post-Volcanic Winter Warming and the Role of Internal Climate Variability

Volcanic eruptions are believed to affect the Eurasian and North American winter temperatures (Shindell et al. 2004; Stenchikov et al. 2002; Schneider et al. 2009). In the first winter following the 1991 eruption of Pinatubo, an increase in surface temperature reaching up to 3 °C was observed on the Eurasian continent, which was attributed to the recovery of global temperature following a volcanic eruption (e.g., Robock, 2002). While this 1991–1992 winter warming pattern could be considered to be triggered by natural climate variability (e.g., Polvani et al. 2019), Eurasian winter warming pattern was also seen in the first NH winter after three other tropical volcanic eruptions (Xing et al. 2020). This post-eruption European warming was also seen in 500-year multi-proxy reconstructions of 15 major tropical eruptions (Fischer et al. 2007). These responses are consistent with a forced volcanic response of the NAO. Some modeling studies have reported the cooling over the Middle East and North Africa after large eruptions, suggesting that it is part of a circulation response of same origin as the winter warming in Eurasia (Robock and Mao, 1992; Robock, 2002; Shindell et al. 2004; Osipov et al. 2016; Dogar et al. 2017; 2019; Dogar, 2020). However, there are only a few studies available that analyzed the underlying possible causes of the seasonal climate variability triggered by volcanic eruptions, that is winter warming over Eurasia and cooling patterns over Middle East and North Africa (MENA) respectively (e.g., Haywood et al. 2013; Dogar et al. 2017), so the dynamic feedbacks processes and forced circulation changes still remain poorly understood. The Eurasian winter warming teleconnection is also potentially related to stratosphere−troposphere interaction. It has been shown that a tropical volcanic eruption can directly warm up the lower part of the tropical stratosphere since the aerosol clouds interact and absorb incoming near-infrared (NIR) and outgoing longwave radiation. Volcanic aerosols also deplete polar ozone by affecting ozone photochemistry in stratosphere. As solar radiation is absorbed by ozone in stratosphere, ozone depletion will lead to lower temperatures (Stenchikov et al. 2002) in the polar region. Resultant stratospheric warming at low-latitudes and polar cooling intensify the meridional temperature contrast over the NH, eventuating in a strengthened NH winter polar vortex (Figure 9a). This strengthened polar vortex, potentially warms Eurasia by entrapping tropospheric wave energy (Robock, 2000; Butler et al. 2014; Perlwitz and Graf, 1995; Raible et al. 2016). Mostly the CMIP5 (e.g., Xing et al. 2020) as well as CMIP6 models (Liu et al. 2020, Figure 9) can simulate this low-latitude stratospheric warming. The strengthened polar vortex, however, is weak in the models compared to the reanalysis (Marshall et al. 2009), posing a challenge for the current simulation of stratospheric teleconnection.

Current GCMs are able to reproduce the direct responses to large tropical eruptions (Trenberth and Dai, 2007; Iles and Hegerl, 2014; Stevenson et al. 2016; Liu et al. 2016), but they

still lacks in simulating the indirect responses caused by post-volcanic circulation changes, that could be related or unrelated to volcanism (Ding et al. 2014; Marshall et al. 2009; Driscoll et al. 2012; Maher et al. 2015; Zambri et al. 2017; Wang et al. 2018; Xing et al. 2020; Polvani et al. 2019).

There is emerging debate on the volcanic indirect effect caused by circulation changes that apparently produced warming effects in the first two winters following tropical eruptions over Eurasia and North America. Previous studies have linked this Eurasian and North American warming (up to 3°C) of 1982-1983 and 1991-1992 winters to the 1982 El Chichon and 1991 Pinatubo eruptions (Robock and Mao, 1992; Xing et al. 2020). Using a 500-year multi-proxy reconstruction, Fischer et al. (2007) also showed this warming pattern that occurred following major tropical eruptions. This eruption−Eurasian-warming has been assumed to be due to post-eruption stratosphere−troposphere interaction that caused strengthening of the stratospheric polar vortex and associated positive phase of North Atlantic Oscillation (Stenchikov et al. 2002). However, recent studies have argued that such winter warming may simply be a result of internal variability (Polvani et al. 2019) caused by the positive phase of the Pacific North American pattern (PNA) favored by the ongoing positive ENSO events (El Niños) at the time of the eruptions (Fujiwara et al. 2020; Wunderlich and Mitchel, 2017). The El Niño events could also have favored a North Atlantic Oscillation response through stratospheric pathways (Marshall et al. 2009; Ineson and Scaife, 2009; King et al. 2018) and hence could explain the Eurasian warm winters following El Chichon and Pinatubo eruptions. However, other studies have demonstrated that large volcanic eruptions enhance the probability and strength of El Niño events (Pausata et al. 2015; 2020; Stevenson et al. 2016); hence, volcanic eruptions may still be the initial trigger for the warm winters at high latitudes. No study has hitherto investigated this chain of teleconnections. Moreover, the ENSO-NAO teleconnection itself still remains controversial. Moreover, the initial conditions of both the atmosphere (e.g., Quasi-biennial Oscillation (QBO) phase in the stratosphere) and the ocean (e.g. ENSO) at the time of the eruptions can further complicate the atmospheric circulation response to volcanic eruptions. For example, the studies of Zeng (2003), and Dogar et al. (2017, 2019) assessed the ITCZ seasonal shift and subsequent weakening of monsoon following strong ENSO forcing and reported that ITCZ southward shift over the south Asian monsoon belt is caused due to El Niño–like SST conditions, which could be related or unrelated to volcanism. These studies strongly suggest that the ITCZ response to internal or external climate forcings (i.e., ENSO or volcanism respectively) or their concurrent effect through ENSO-volcano linkage requires specifically designed coupled model sensitivity experiments in addition to VolMIP for better understanding of ENSO-volcano linkage. Modeling studies also show a strong negative/positive NAO–like pattern over the Atlantic Ocean following strong El Niño/La Nina forcing (Dogar et al. 2017, 2019). This NAO-like North Atlantic ENSO response may largely be caused by ENSO

teleconnections through stratospheric pathways (e.g. Ineson and Scaife 2009) or it could simply be an extension of the PNA–like pattern (e.g. Bulić and Kucharski 2012). This negative NAO pattern produces significant impact and induces warm and wet anomalies over Southern Europe extending to Middle East and North African region (Dogar et al. 2017, 2019). Since the origin of winter warming is elusive, therefore, further research is highly needed to disentangle the climatic response to volcanic eruptions and improve our understanding of tropical-to-extratropical teleconnections. For this purpose a set of experiments as shown in the schematic (Figure 10, panel A and B) is proposed. It involves ensemble experiments with and without volcanic forcing (initialized with different ENSO states to see the effect of ocean preconditioning) that could be used to disentangle volcanic direct and indirect circulation changes. Such idealized experimental setup will also help us to figure out the recent controversies whether post-volcanic Eurasian and North American warming is related or unrelated to volcanism (Polvani et al. 2019; Fujiwara et al. 2020).

9. Summary and Discussion

Study of volcanism is very important due to their direct radiative and indirect (through their impacts on large scale circulation changes, e.g., ENSO and NAO) climatic effects. A better understanding of volcanism and its impacts on ENSO could help in reliable prediction of the ENSO response to future eruptions, therefore accurate detail of volcano-ENSO linkage is highly needed to determine the actual magnitude of the climatic response controlled by these important forcing factors. Reliable observational data for the volcanic eruptions occurring in the satellite era is available, which provide sufficient details for robust model-based simulation of the volcanic-induced climate response. However, for volcanic eruption events of the past, details of stratospheric aerosol size distribution and eruption timing need to be reconstructed from climate proxy data (Sigl et al. 2015). Although much work has been done so far using PMIP3 and CMIP5 based protocols to improve the reconstructions of the past volcanic forcing (Toohey et al. 2016), clarity about the timing (Stevenson et al. 2017) and latitudinal position (Fasullo et al. 2019) of the volcanic event and its forcing properties is still elusive (Ding et al. 2014; Marshall et al. 2018; Gautier et al. 2019). Hence, to better understand the impact of volcanism on ENSO, it is necessary to have refined reconstructions of both the ENSO variability and volcanic forcing. We note that both the seasonality of the radiative effects of volcanism (e.g., Toohey et al. 2011) and seasonally varying strength of ENSO (e.g., Nicholls, 2008; Lai et al. 2018; Zheng et al. 2010) have the potential to modify the strength of the response of ENSO to volcanism, but these effects have not been explored in detail.

Despite some discrepancies, most of the past studies using paleoclimate proxy data show an El Niño–like warming in the eruption year (about 70 % of reconstruction data) when specified with consistent volcanic eruptions dates and none of the ENSO reconstructions show a significant La Niña–like response. However, some reconstructions (Table 1) that show a significant El Niño–like

conditions during eruption year also show significant La Niña–like cooling a few years before or after the volcanically driven El Niño–like SST warming (McGregor et al. 2020). This suggests that the La Nina response seen in observations, paleoclimate proxy records, and model simulations after initial El Niño could be a reflection of oscillatory nature of ENSO dynamics by which La Niña events generally follow El Niño events (Okumura & Deser, 2010; e.g. Ohba & Ueda, 2009). It further emphasize that at least a portion of such signal seen in reconstructions could be attributed to natural variability (Polvani et al. 2019; 2020) rather than to volcanic forcing and large ensemble experiments are still needed to quantify the relative roles of internal and forced response. This also suggests that volcanic effects could persist for more than one year beyond the eruption. Various paleoclimate studies are available so far to reconstruct ENSO relationship to volcanism and mostly they show varying results. For instance, Dee and Steiger, (2022) tested the volcanism-ENSO linkage in the past 2000 years long records of PHYDA product and noticed a weak tropical Pacific response following large tropical volcanism resembling to El Niño. Moreover, inconsistencies were noticed in magnitudes and spatial patterns between climate models and PHYDA regarding ENSO-volcano linkage.

We noticed an emerging consensus in CGCM based studies that investigated the impact of tropical volcanic forcing on ENSO, with the vast majority showing an El Niño–like warming in the year after a tropical eruption (McGregor et al. 2020). Despite the coherent responses, the CMIP5 and CMIP6 model response is significantly weaker than the observational composite (Liu et al. 2020; Xing et al. 2020). Nevertheless, some recent studies based on CMIP5 simulations showed significantly larger (by 40-49 %) eruption-induced cooling than observations (Chylek et al. 2020). This disparity could be either because of the extent of the response is inaccurately modeled, or due to the coincidental occurrence of eruptions and El Niño events and/or model poor response to this coincidental interaction and linkage to other possible concurrent natural variability signals (e.g. Nicholls, 1988; Schneider et al. 2009; Driscoll et al. 2012; Polvani et al. 2019). Disparities in model responses and their inconsistency with observations and proxy-based reconstruction could also be partly related to the input of volcanic ash, which is neglected so far. Recently, it has been suggested that the contribution of volcanic ash should be taken into account in volcanic simulations as it turns out to be a key factor, but has been completely neglected due to its short lifespan (Zhu et al. 2021). Ash-rich particles dominate the optical properties of the volcanic cloud for at least the first two months, and therefore the initial lifetime of sulfur-rich gases is determined by the absorption of sulfur dioxide onto the ash, instead of the reaction with OH as generally assumed. This study further shows that approximately 43% more removal of volcanic sulfur from the stratosphere occurs within 2 months due to heterogeneous sulfur dioxide chemistry on volcanic ash than without.

While most CGCMs show El Niño–like response, the exact dynamical causes of the response is still elusive. Several mechanisms (e.g., ocean dynamical thermostat, wind stress curl,

and ocean-land temperature changes) have been proposed that apparently explain the projection of volcanic radiative cooling onto the ENSO variability, and different models favor different mechanisms. Apparently, the inconsistency among models is attributed to differing model dynamics, difference in feedbacks processes (e.g., Soden et al. 2002) and parameterizations or differing experimental design. Thus, the modeled response appears to be the sum or balance of multiple feedback projections. Since the balance of feedbacks varies between models (e.g., Joshi and Shine, 2003; Lloyd et al. 2011; Soden et al. 2002), therefore, how ENSO reacts to volcanic forcing may also vary across models.

Compared to tropical eruptions, there are fewer studies available to date that investigated the impact of extratropical Northern/Southern Hemisphere (NH/SH) volcanic eruptions on ENSO (Schneider et al. 2009; Pausata et al. 2015, Stevenson et al. 2016; Liu et al. 2018; Zuo et al. 2018). These studies are consistent and show El Niño–like conditions emerging in the first year following NH eruptions (e.g., Stevenson et al. 2016; Pausata et al. 2015, 2016). Cold conditions in the equatorial Pacific are more likely to appear following SH eruptions, but this could not be similar to typical dynamical La Niña–like response (Stevenson et al. 2016; Pausata et al. 2020). ITCZ shift due to post-eruption cooling has been proposed as the leading mechanism for the ENSO response (Pausata et al. 2020; Stevenson et al. 2016), while the other mechanisms (the ocean dynamical thermostat, the cooling of tropical northern Africa or the Maritime continent) commonly invoked to explain the post-eruption ENSO response appear to be of secondary importance (e.g., Ward et al. 2020; Pausata et al. 2020). A La Niña–like cooling signature following volcanic-induced El Niño–like pattern is also reported in response to extratropical volcanic forcing, which is in agreement with observations and model simulations (e.g., Okumura & Deser, 2010; Ohba & Ueda, 2009). These results suggest that extratropical volcanic forcing could potentially influence ENSO for few years beyond an eruption. In conjunction to this, some recent modeling studies have also analyzed the potential role of ocean circulation about volcano-ENSO linkage especially for high-latitude eruptions and reported that this volcanically driven ENSO variability persisting for several decades beyond the eruption could be attributed to volcanically forced changes in Atlantic Meridional Overturning Circulation and associated changes in ocean heat content and sea level rise (e.g., Church et al. 2005; Stenchikov et al. 2009; Mignot et al., 2011; Pausata et al. 2015; 2020). The role of ocean circulation is very important in terms of ENSO variability and response to volcanism as ocean accumulates the signal of external forcing and responds at multiple time scales (e.g., Church et al. 2005; Stenchikov et al. 2009). As tropical volcanism also caused comparable perturbations in ocean circulation, especially in ocean heat content and sea level rise, (Church et al. 2005; Stenchikov et al. 2009; Mignot et al., 2011; Zanchettin et al. 2012; Dogar et al., 2020; Swingedouw et al. 2015), therefore one would anticipate predicting similar modulation of ENSO following tropical volcanism.

Our understanding of the evolution of ENSO and what ultimately leads to the occurrence of El Niño has improved considerably. Basically it is westerly wind anomalies over the western central equatorial Pacific that trigger Kelvin wave response leading to dynamically forced warming in the easternmost Pacific. It always starts with central Pacific warming, though (Graf 1986; Lai et al. 2016, 2018; Fadnavis et al., 2021).

We noticed that the coupled model simulations show a southward (northward) shift of ITCZ following strong NH (SH) eruptions. Moreover, strong tropical eruptions (e.g., El Chichon and Pinatubo) also show a southward shift of ITCZ and associated weakening of South Asian monsoon in first two post-eruption summer seasons both in the observation analysis and high-resolution atmospheric model (HiRAM) simulations (Dogar and Sato, 2019). This ITCZ southward (northward) shift is also seen following strong El Niño (La Nina) conditions in AOGCM simulations with intermediate complexity (Dogar et al. 2017). This suggests that further systematic coupled model experiments are needed to better understand these interfering effects of ENSO and volcanism on the upward branch of Hadley Cell (i.e., ITCZ, e.g., Dogar, 2018). Similarly, varying mechanisms have been proposed regarding post-eruption high-latitude winter warming effect, such as this warming is argued to be caused by ENSO-induced NAO–like pattern or through volcanic-induced NAO–like pattern. This North Atlantic NAO-like ENSO response is also interpreted as an extension of the PNA pattern (e.g. Brönnimann et al. 2007; Bulić and Kucharski 2012), or it could simply be caused by ENSO teleconnections through a stratospheric pathways (e.g. Ineson and Scaife 2009). El Niño and La Nina events seem connected with extra-tropical climate anomalies through Pacific North American teleconnection pattern (Ropelewski and Halpert, 1986), therefore, it is of prime importance to understand the causes of interannual variability associated with ENSO and other climate phenomena (e.g., PNA and NAO) to fully understand the long-term effects of, for example, changes in volcanism on teleconnections (e.g., ENSO) and associated variations in global climate. Since the exact origin of post-eruption winter warming is still elusive, therefore, idealized experiments in addition to VolMIP as proposed in Figure 10 are needed to enhance our understanding on the complex ENSO-volcano linkage and associated climatic impacts.

A thorough assessment of the past literature shows that, in general, CMIP based models show agreement on the underlying mechanisms of El Niño–like response triggered by tropical eruptions, however, uncertainties still exist among modeled responses to volcanism happening in the tropics and extratropics. The causes of such disparities are still elusive, however, apparently these could be related to intermodal differences in experimental design, the quantity of ensemble members including methods used to construct the ensembles, model resolution, differing model top, input volcanic forcing data including its magnitude, seasonality, and the aerosol optical properties associated with sulfate injection (e.g., Stevenson et al. 2017; Toohey et al. 2011; Collins et al. 2010; McGregor & Timmermann, 2011; Zhu et al. 2021; Ohba et al. 2013). Moreover, model's limited

ability to simulate the contribution of internal variability related to large-scale circulation changes could add further to this uncertainty (Marshall et al. 2009; Driscoll et al. 2012; Zambri et al. 2017). Ocean precondition state (taking into account ENSO-types) at the time of eruption also adds to this ENSO-volcano complex linkage and intermodal inconsistency in projection of this nexus. Moreover, CP-type El Niño onsets may respond to volcanism more intensely than EP-type El Niño onsets. Response of Hadley and Walker circulations and associated regional monsoonal rainfall are also largely different for CP and EP-type ENSOs. This suggests the need for further studies on model sensitivity to radiative forcing with consistent experimental protocol and a large number of models and a large number of ensemble members. These idealized volcano-ENSO perturbation experiments designed to accurately account for the effect of natural variability (e.g., ENSO, PNA and NAO, Figure 10), in addition to the Model Intercomparison Project on the climate response to volcanic forcing, VolMIP (Zanchettin et al. 2016), will permit future research to emphasize on response differences that apparently originate from intermodal physical and dynamical differences.

10. Concluding Remarks

Past literature based on short paleoclimate records and coupled model simulations suggest a significant eastern Pacific warming resembling an El Niño–like response during the eruption year and a lagged La Niña–like response few years after the eruption. However, long range climate reconstructions based on newly developed PHYDA product, spanning past 2000 years show a weak El Niño–like response of the tropical Pacific following volcanism. This is partly attributed to the statistical approaches employed to evaluate proxy based reconstructions as they seems sufficiently less sensitive in capturing ENSO response especially when there are strong chances of volcanic signal modulation with concurrent ENSO signal and the possibility of the interaction with internal variability caused by other large scale circulation changes (e.g., PNA and NAO). We further noticed that the ENSO response to volcanism is very sensitive to ocean preconditioning (especially different ENSO-types, i.e., EP and CP), eruption timing, position and magnitude. Moreover, stronger volcanic eruptions are expected to cause more significant ENSO response. We further noticed that some mechanisms of ENSO-volcano linkage still remain elusive. For example, how radiative cooling of tropical volcanism is projected onto ENSO contingent to the coincidental ENSO events unfolding at the time of the eruption. There are fewer observations and climate proxy records available to evaluate the effects of extratropical volcanism on ENSO. Nevertheless, model-based studies suggest that extratropical Northern (Southern) eruptions trigger a response similar to that of El Niño (La Niña). Emergence and significant amplification of El Niño-like conditions are also projected in a model simulation with RCP-8.5 future scenario following strong tropical eruptions of the size of Tambora 1815, and associated reduction in monsoonal rainfall (e.g., African and Asian-Australian monsoons) largely due to the post-volcanic land-ocean thermal contrast mechanism.

The specific cause of post-eruption winter warming is still elusive, however, recent findings suggest that the large-scale circulation changes concurrently occurring during volcanism could be the potential source of high-latitude winter warming over Eurasia and North America. We noticed that significant studies are available that highlight anthropogenic–driven ENSO changes and those derived by volcanism, however, combined interaction and ENSO response to both these external forcings (i.e., anthropogenic and volcanism) is not explored yet. Therefore, further research in this direction is recommended with consistent experimental protocol using multi-models and large ensembles accounting for the effects of internal variability and other large scale circulation changes, to explore the ENSO response to tropical and extratropical volcanism and to better understand whether post-eruption high-latitude winter warming is related or unrelated to volcanism.

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Declarations

Conflict of Interest

The authors declare that there is no conflict of interest.

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Table 1: Details of the ENSO reconstructions, and their correlation with the observed ENSO variability as denoted by the Southern-Oscillation Index (SOI) over the period 1900–1977 (Source: McGregor et al. 2020).

Proxy Number	Start Year	End Year	Reference	Source Proxy Location	Source Proxy Type	Correlation with SOI
1	1706	1997	Stahle et al. (1998)	Pacific Basin	Tree ring	0.76
2	1408	1978	Cook (2000)	North America	Tree ring	0.73
3	1650	1990	Mann et al. (2000)	Near global tropics	Mixed	0.78
4	1590	1990	Evans et al. (2002)	Indo-Pacific Basin	Coral	0.67
5	1800	1990	Evans et al. (2001)	America	Tree ring	0.67
6	1300	1978	Cook et al. (2008)	North America	Tree ring	0.75
7	1727	1982	Braganza et al. (2009)	Pacific Basin	Mixed	0.73
8	1525	1982	Braganza et al. (2009)	Pacific Basin	Mixed	0.65
9	1650	1977	McGregor et al. (2010)	Pacific Basin	Mixed	0.83
10	1607	1998	Wilson et al. (2010)	Tropical Pacific	Mixed	0.58
11	1540	1998	Wilson et al. (2010)	Pacific Basin	Mixed	0.48
12	900	2002	Li et al. (2011)	North America	Tree ring	0.6
13	1150	1998	Emile-Geay et al. (2013a, 2013b)	Near global tropics	Mixed	0.8
14	1150	1998	Emile-Geay et al. (2013a, 2013b)	Near global tropics	Mixed	0.83
15	1150	1998	Emile-Geay et al. (2013a, 2013b)	Near global tropics	Mixed	0.82
16	1301	2005	Li et al. (2013)	Pacific Basin	Tree ring	0.67
17	1607	1997	Tierney et al. (2015)	Tropical Pacific	Coral	0.74

Figure Legends:

Figure 1: Observed SST response to the five main volcanic eruptions during 1870–2010 (i.e., Krakatau (1883), Santa Maria (1902), Mt Agung (1962), El Chichon (1982), and Pinatubo (1991)). SST anomalies (SSTA, ^{o}C) are computed using the preceding 5-year climatology, and the resulting anomalies are plotted relative to the tropical average (20°N–20°S). (a) Evolution of the composited Niño-3.4 (5°S–5°N, 170°W–120°W) SSTA plotted over the 2-year period including the five largest volcanic eruptions during 1870–2010 in HadISST observations (black line). The red dots denote when the five events have anomalies of the same sign. An arrow indicates the dates and magnitude of the selected eruptions, based

on AOD by Gao et al. (2008). (b) Same as (a) but shown as a longitude-time section. The black rectangle denotes the Niño-3.4 region during October-November-December. Stippling highlights times and locations where the five eruptions display anomalies of the same sign and the contour corresponds to the 90% significance level of this anomaly following a two-tailed Student's *t*-test. Note that the composites maintained a common seasonality (i.e., the calendar months of each eruption were aligned despite the differing eruption months) due to the seasonally synchronized nature of ENSO dynamics (Source: Khodri et al. 2017).

Figure 2: Observed boreal-winter SAT anomaly after the five strong volcanic events (Krakatau, Santa María, Agung, El Chichón, and Pinatubo). Composite SAT anomaly (shading; K) with respect to the five years preceding each eruption during the first boreal winter after the five selected eruptions in (a) 20CRv2c, (b) GISTEMP. Stippling indicates temperature anomaly significant at the 95% confidence level.

Figure 3: Observed and simulated El Niño relationship with volcanism. Five month running mean of Niño 3.4 index (K; dotted line: HadSST1; solid line: HadSST2; dot-dashed line: ERSSTv5) and 850 hPa WCEP (140° E–180°, 5° S–5° N) zonal wind (U, ms−1) anomalies in observations and reanalysis and in SEA composite of 41 ensemble members of CESM-LE (dashed line) for Agung (1963), El Chichón (1982), and Pinatubo (1991) eruptions. Solid part of the curve denotes simulated anomaly significant above the 95% confidence level. Monthly zonal-mean AOD before and after the eruptions for these eruptions are obtained from Ammann (2003). Year (0) denotes the eruption year, and year (1) is the first year after the eruption (Source: Chai et al. 2020).

Figure 4: Superposed Epoch Analysis of the last millennium reanalysis (LMR) Niño 3.4 reconstructions around the 13 events when the Palmyra coral record is available, a) coral predictors only, b) six best tree-ring based Niño 3.4 predictors previously identified by Li et al. 2013 (Li13b6), and c) corals+Li13b6 predictors. Solid curves with dark dots denote the composite mean, and the light dots denote the Niño 3.4 anomaly at each year for each individual event. The light gray dashed curves denote the 1%, 5%, 10%, 90%, 95%, and 99% quantiles of the composite means from 1000 bootstrap drawn from non-volcanic years (Zhu et al. 2022).

Figure 5: Composited ensemble-mean seasonal average surface temperature anomalies (relative to tropical mean: 20°N–20°S) and rainfall anomalies (contours at intervals of 0.2 mm/day; zero contours are excluded) with surface wind (m/s; vector). The ensemble mean maps are calculated from 32 CMIP5 models that are each composited around five strong volcanic events (i.e., Krakatau, Santa María, Agung, El Chichón, and Pinatubo) where the eruption begins in year 0. DJF (0/1) is peak of the strong tropical volcanic forcing composite (Source: McGregor et al. 2020).

Figure 6: Transition to La Niña from tropical eruption-induced El Niño mode and internal El Niño mode. Shown are the composite NINO3 index for 25 tropical eruptions during the period 501 to 2000 AD (thick red line) and for the El Niño in the control run (thick blue line), as well as the associated zonal wind anomalies (dashed lines) averaged over the western Pacific (5°S–5°N, 120°E–150°E). "1" denotes 1 year after each eruption, and "2", 2 years. The El Niño in the control run is defined when the boreal winter (December–February average) NINO index is above one standard deviation. Each variable is normalized by its maximum value in years "1" and "2". The year is defined as the eruption year when its annual aerosol is larger than the 2 years before and after it. When the eruption starts late in the year, e.g., November or December, it has maximum aerosol density in the following year; in such case, the following year is considered as the eruption year (Source: Liu et al. 2018).

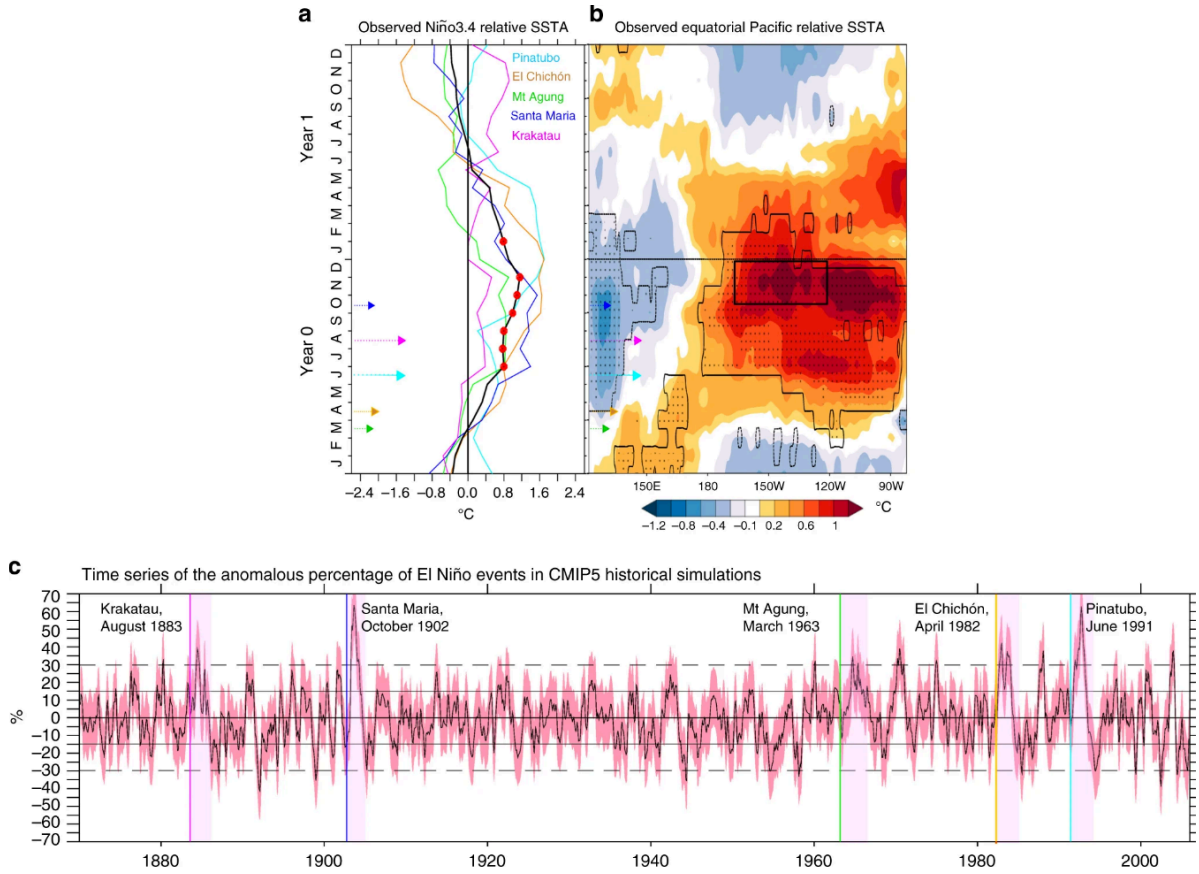
Figure 7: CESM version 1.0 (CESM1) model simulated SST anomaly evolutions after different eruptions. The composites of normalized 3-month-mean SST anomalies (shading), and 850-hPa wind anomalies (vectors) since the first winter after the NH (a), the tropical (b), and the SH (c) eruptions. "0" denotes the year of each eruption, and "+1" indicates 1 year after the eruption.

Figure 8: CESM version 1.0 (CESM1) model simulated oceanic responses to different eruptions. The normalized composite summer-mean (June–August) surface currents and surface (0–20 m) upwelling anomalies one year after the NH (a), the tropical (b), and the SH (c) eruptions (Source: Liu et al. 2018).

Figure 9: Stratospheric responses to tropical volcanism in CMIP6. Composites of (a) zonally averaged temperature anomalies as a function of latitude and height (shading), and (b) 50-hPa geopotential height anomalies in the first NH winter following the five tropical eruptions for the multi-model mean of the 21

CMIP6 models (shading). The ensemble mean of each model is also shown in (b). Stippling denotes anomalies significant at the 95% confidence level (Source: Liu et al. 2020).

Figure 10: A schematic diagram suggesting two different experiments using a large number of coupled GCMs with large ensemble members with volcanic (i.e., panel A) and non-volcanic forcing (i.e., panel B). The difference of the ensemble average of these multi-model, multi-ensemble volcanic forcing experiments from non-volcanic experiments is required to delineate the volcanic impact (i.e., direct and non-direct) from natural climate variability. Large-scale circulation changes that supposedly play role in high-latitude winter warming are shown in bold red font.



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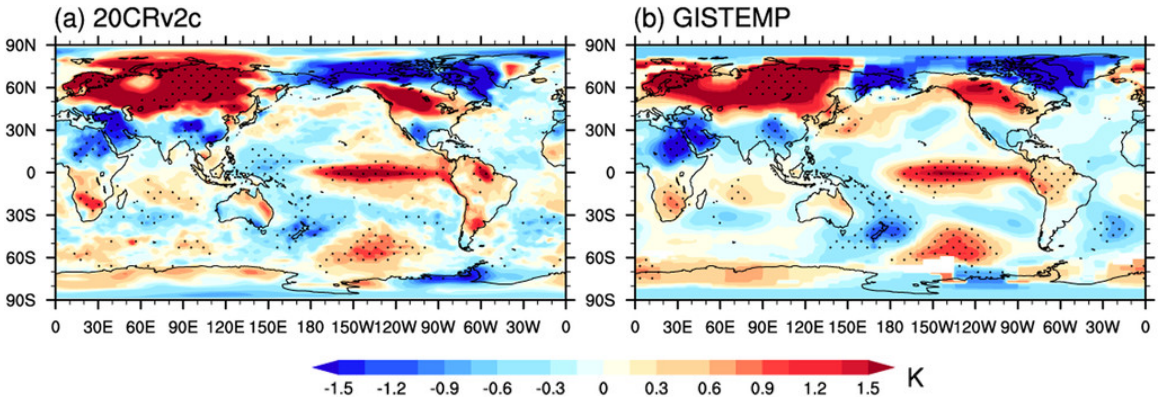

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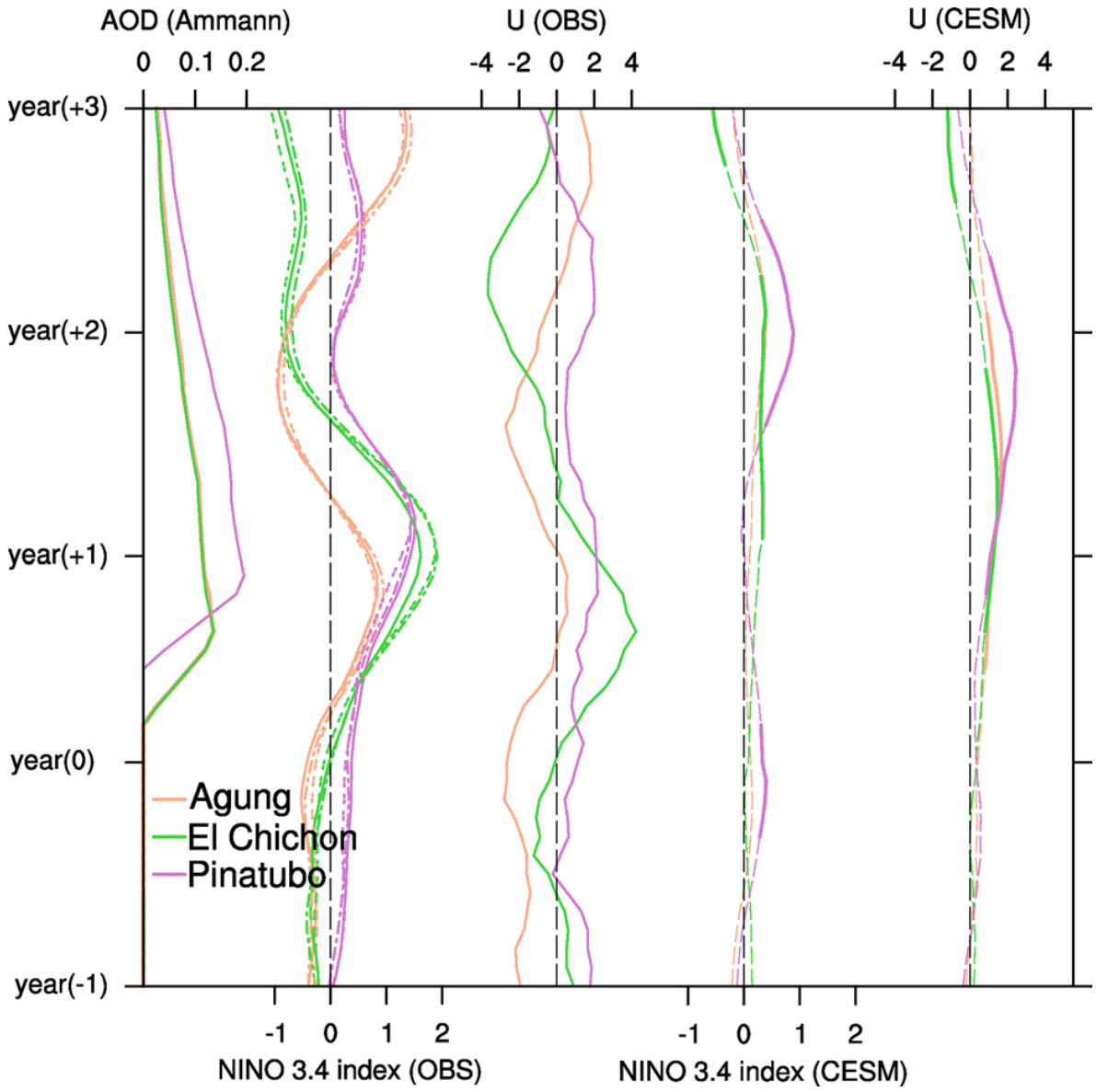

Figure 3: Observed and simulated El Niño relationship with volcanism. Five month running mean of Niño 3.4 index (K; dotted line: HadSST1; solid line: HadSST2; dot-dashed line: ERSSTv5) and 850 hPa WCEP (140° E–180°, 5° S–5° N) zonal wind (U, ms−1) anomalies in observations and reanalysis and in SEA composite of 41 ensemble members of CESM-LE (dashed line) for Agung (1963), El Chichón (1982), and Pinatubo (1991) eruptions. Solid part of the curve denotes simulated anomaly significant above the 95% confidence level. Monthly zonal-mean AOD before and after the eruptions for these eruptions are obtained from Ammann (2003). Year (0) denotes the eruption year, and year (1) is the first year after the eruption (Reproduced from Chai et al. (2020) under a creative commons attribution 4.0 license https://creativecommons.org/licenses/by/4.0/).

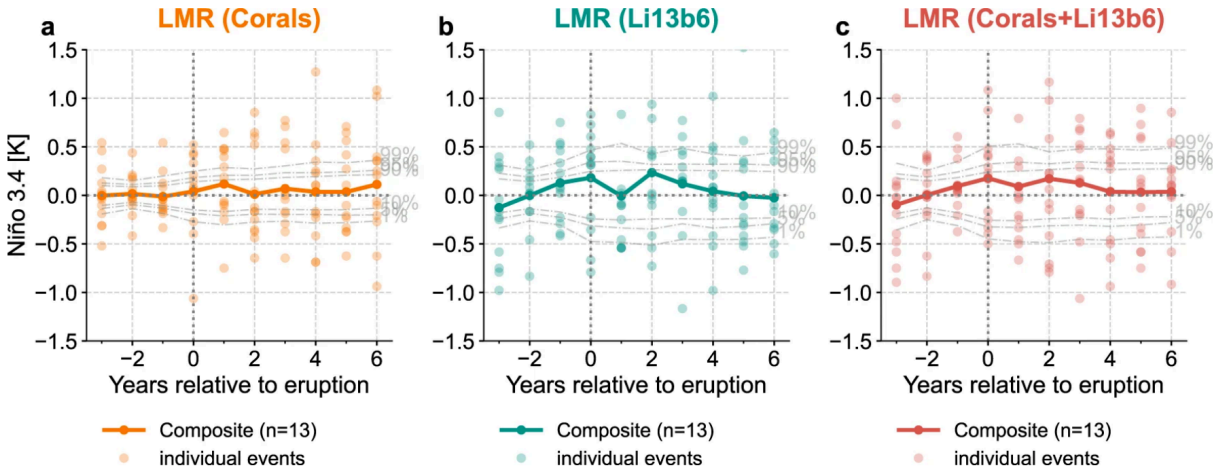

Figure 4: Superposed Epoch Analysis of the last millennium reanalysis (LMR) Niño 3.4 reconstructions around the 13 events when the Palmyra coral record is available, a) coral predictors only, b) six best tree-ring based Niño 3.4 predictors previously identified by Li et al. 2013 (Li13b6), and c) corals+Li13b6 predictors. Solid curves with dark dots denote the composite mean, and the light dots denote the Niño 3.4 anomaly at each year for each distinct event. The light gray dashed curves denote the 1%, 5%, 10%, 90%, 95%, and 99% quantiles of the composite means from 1000 bootstrap drawn from non-volcanic years (Reproduced from Zhu et al. (2022) under a creative commons attribution 4.0 license https://creativecommons.org/licenses/by/4.0/).

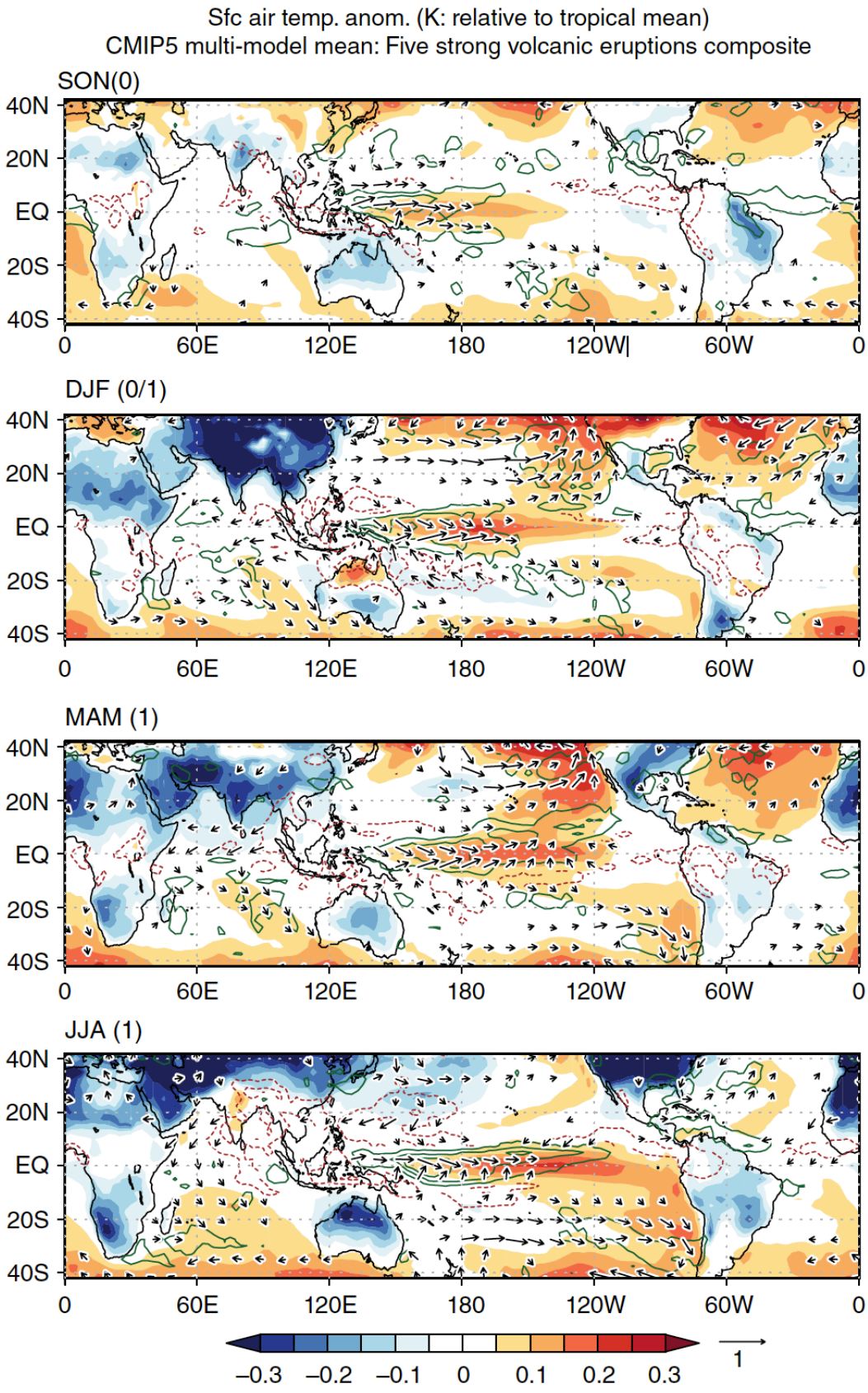

Figure 5: Composited ensemble-mean seasonal average surface temperature anomalies (relative to tropical mean: 20°N–20°S, unit: K) and rainfall anomalies (contours at intervals of 0.2 mm/day; zero contours are excluded) with surface wind (m/s; vector). The ensemble mean maps are calculated from 32 CMIP5 models that are each composited around five strong volcanic events (i.e., Krakatau, Santa María,

Agung, El Chichón, and Pinatubo) where the eruption begins in year 0. DJF (0/1) is peak of the strong tropical volcanic forcing composite (Taken from McGregor et al. (2020). © 2018 American Geophysical Union, used with permission).

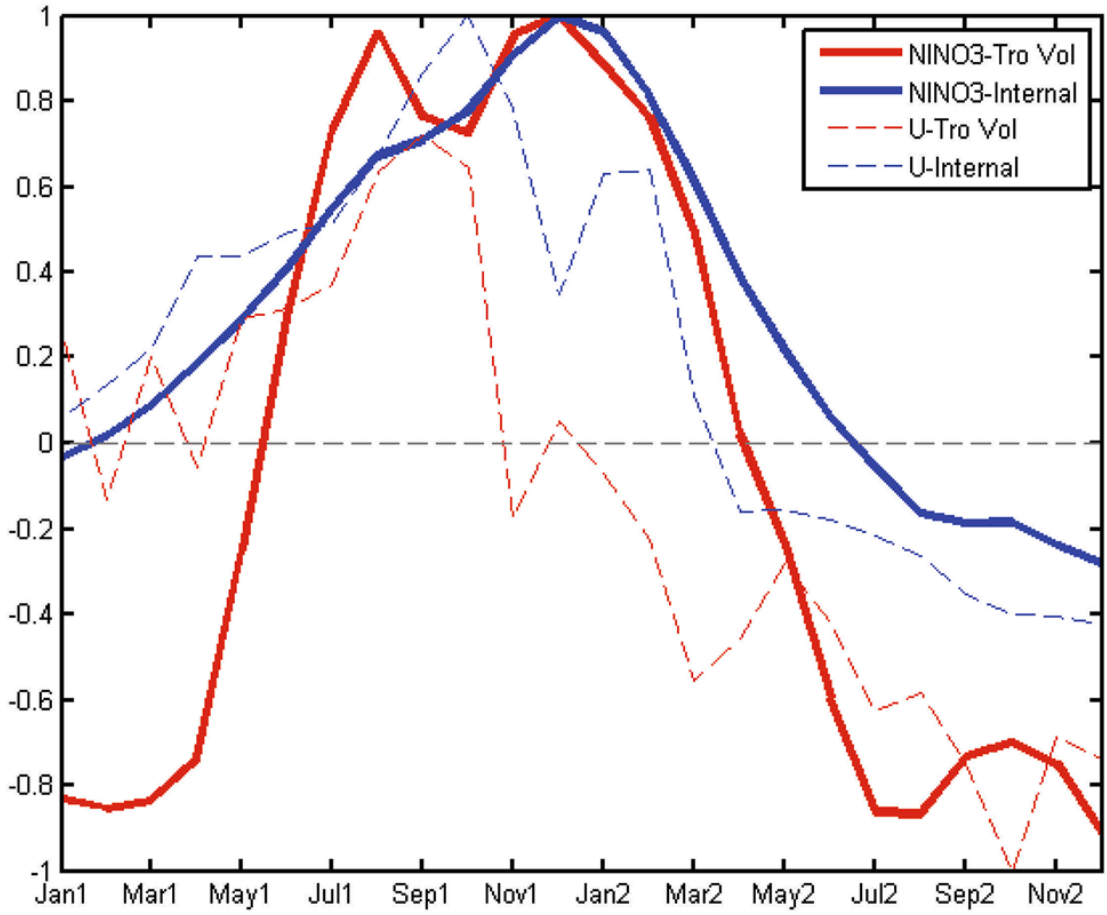

Figure 6: Transition to La Niña from tropical eruption-induced El Niño mode and internal El Niño mode. Shown are the composite NINO3 index for 25 tropical eruptions during the period 501 to 2000 AD (thick red line) and for the El Niño in the control run (thick blue line), as well as the associated zonal wind anomalies (dashed lines) averaged over the western Pacific (5°S–5°N, 120°E–150°E). "1" denotes 1 year after each eruption, and "2", 2 years. The El Niño in the control run is defined when the boreal winter (December–February average) NINO index is above one standard deviation. Each variable is standardized by its maximum value in years "1" and "2". The year is defined as the eruption year when its annual aerosol is larger than the 2 years before and after it. When the eruption starts late in the year, e.g., November or December, it has maximum aerosol density in the following year; in such case, the following year is considered as the eruption year (Reproduced from Liu et al. (2018) under a creative commons attribution 4.0 license https://creativecommons.org/licenses/by/4.0/).

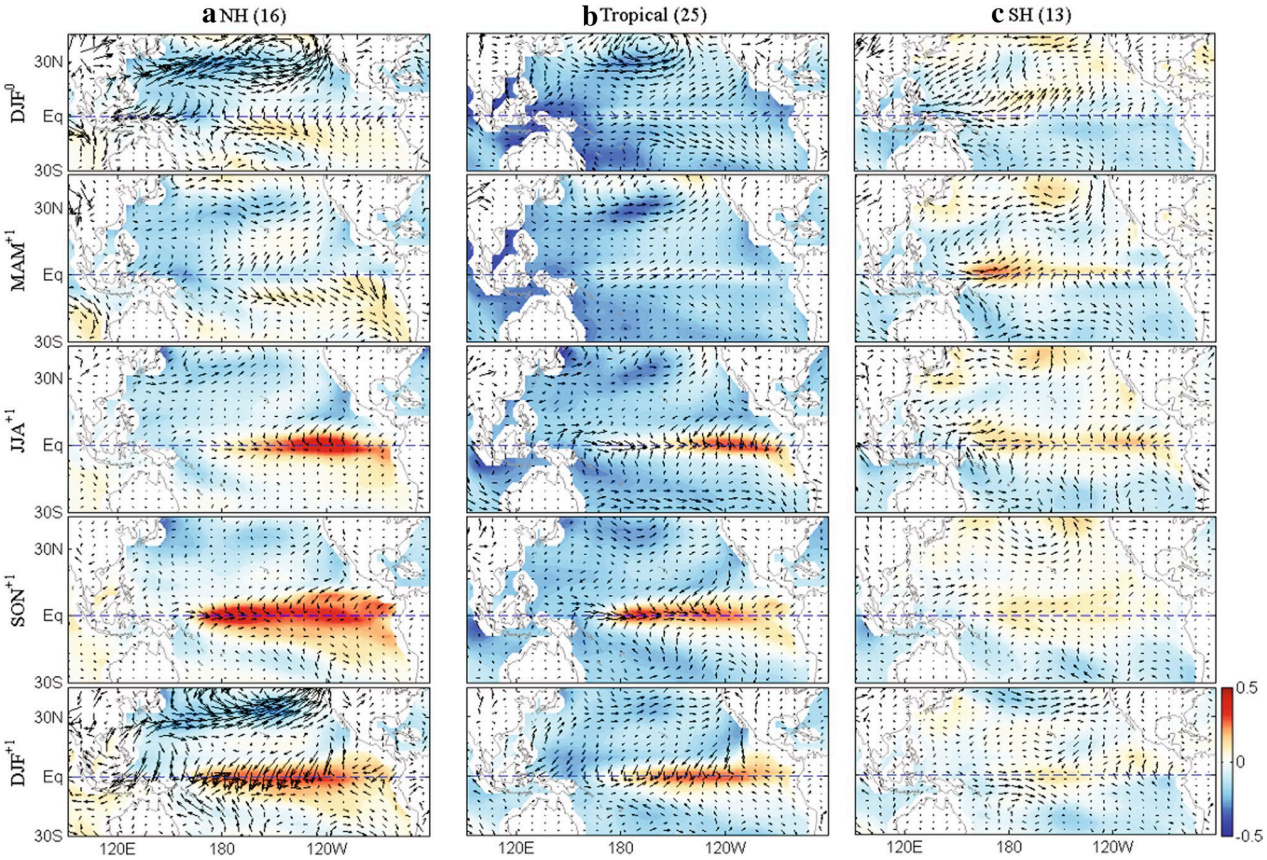

Figure 7: CESM version 1.0 (CESM1) model simulated SST anomaly (K) evolution after different eruptions. The composites of normalized 3-month-mean SST anomalies (shading), and 850-hPa wind anomalies (vectors, m/s) since the first winter after the NH (a), the tropical (b), and the SH (c) eruptions. "0" denotes the year of each eruption, and "+1" indicates 1 year after the eruption. During the simulated 1500 years from 501 to 2000 AD, there were 16 NH, 25 tropical, and 13 SH explosive volcanoes (Reproduced from Liu et al. (2018) under a creative commons attribution 4.0 license https://creativecommons.org/licenses/by/4.0/).

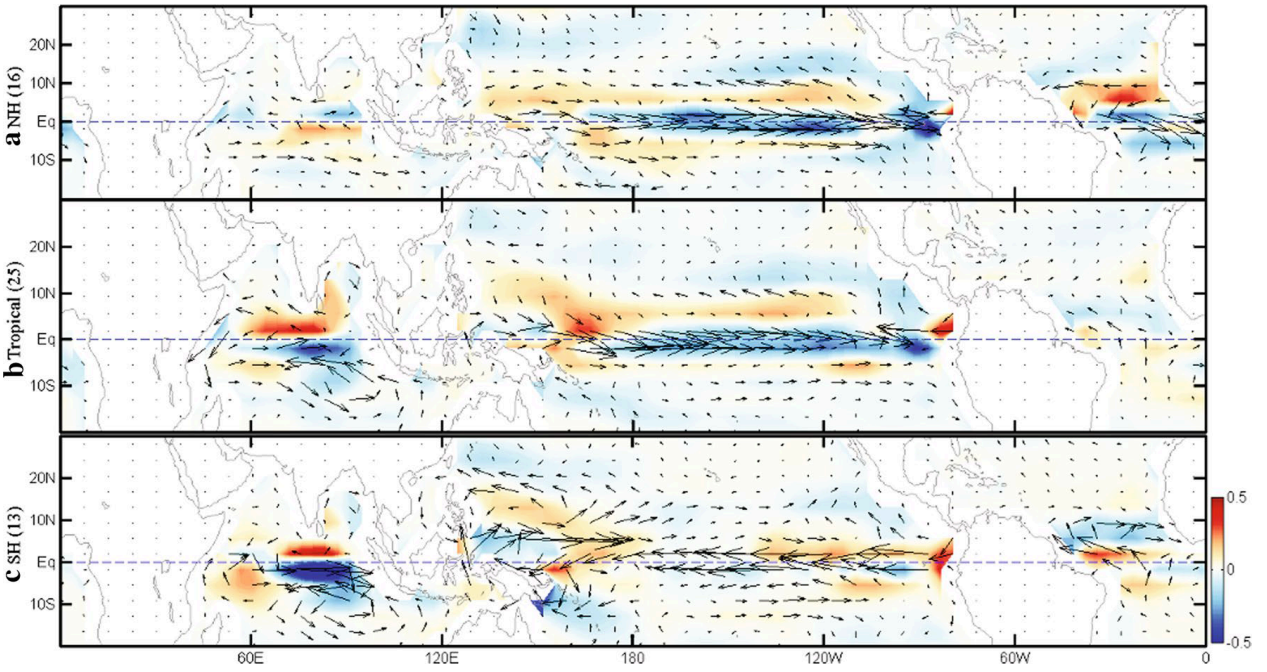

Figure 8: CESM version 1.0 (CESM1) model simulated oceanic responses to different eruptions. The

normalized composite summer-mean (June–August) surface currents (m/s) and surface (0–20 m) upwelling anomalies (shading, K) one year after the NH (a), the tropical (b), and the SH (c) eruptions (Reproduced from Liu et al. (2018) under a creative commons attribution 4.0 license https://creativecommons.org/licenses/by/4.0/).

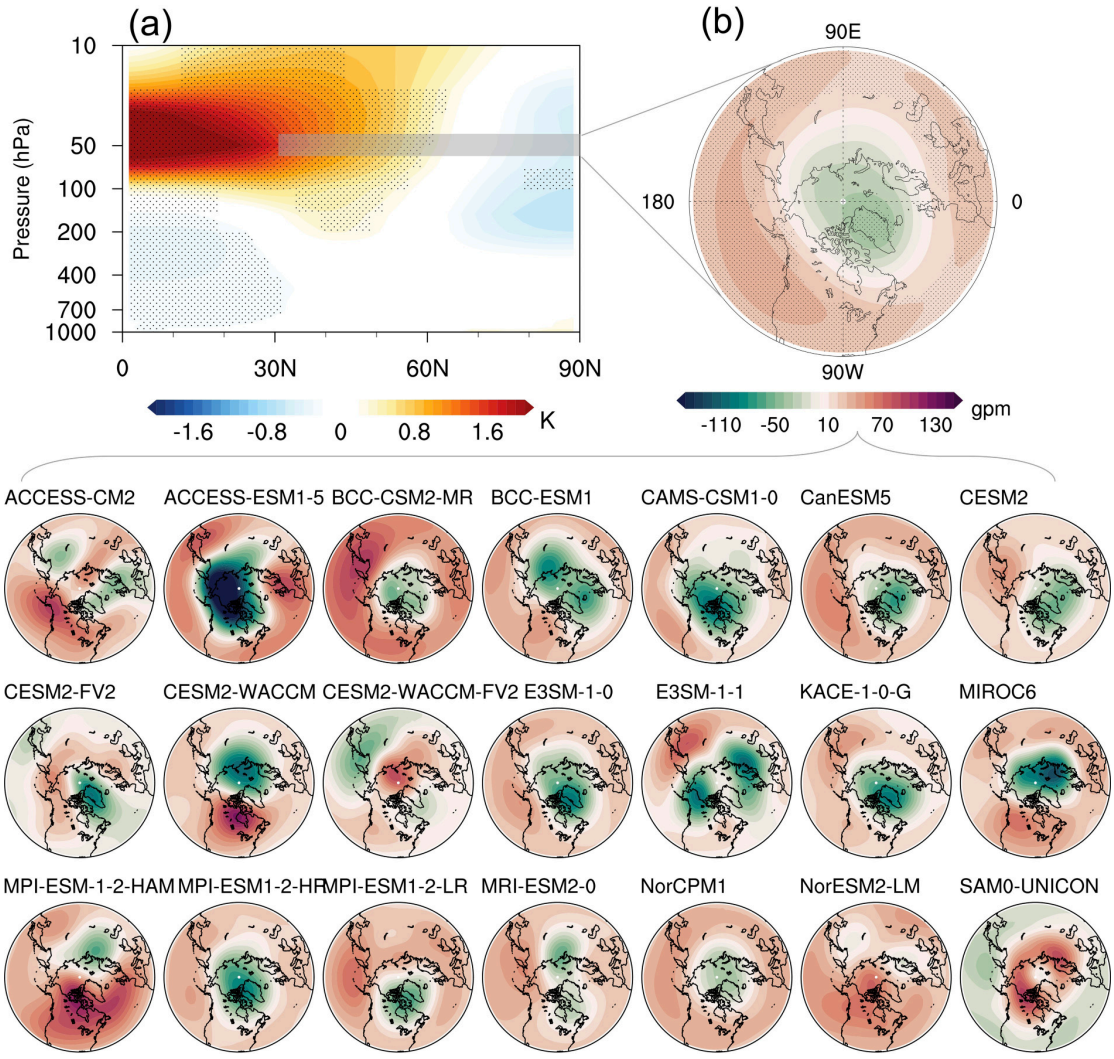

Figure 9: Stratospheric responses to tropical volcanism in CMIP6. Composites of (a) zonally averaged temperature anomalies as a function of latitude and height (shading), and (b) 50-hPa geopotential height anomalies in the first NH winter following the five tropical eruptions for the multi-model mean of the 21 CMIP6 models (shading). The ensemble mean of each model is also shown in (b). Stippling denotes anomalies significant at the 95% confidence level (Reproduced from Liu et al. (2020) under a creative commons attribution 4.0 license https://creativecommons.org/licenses/by/4.0/).

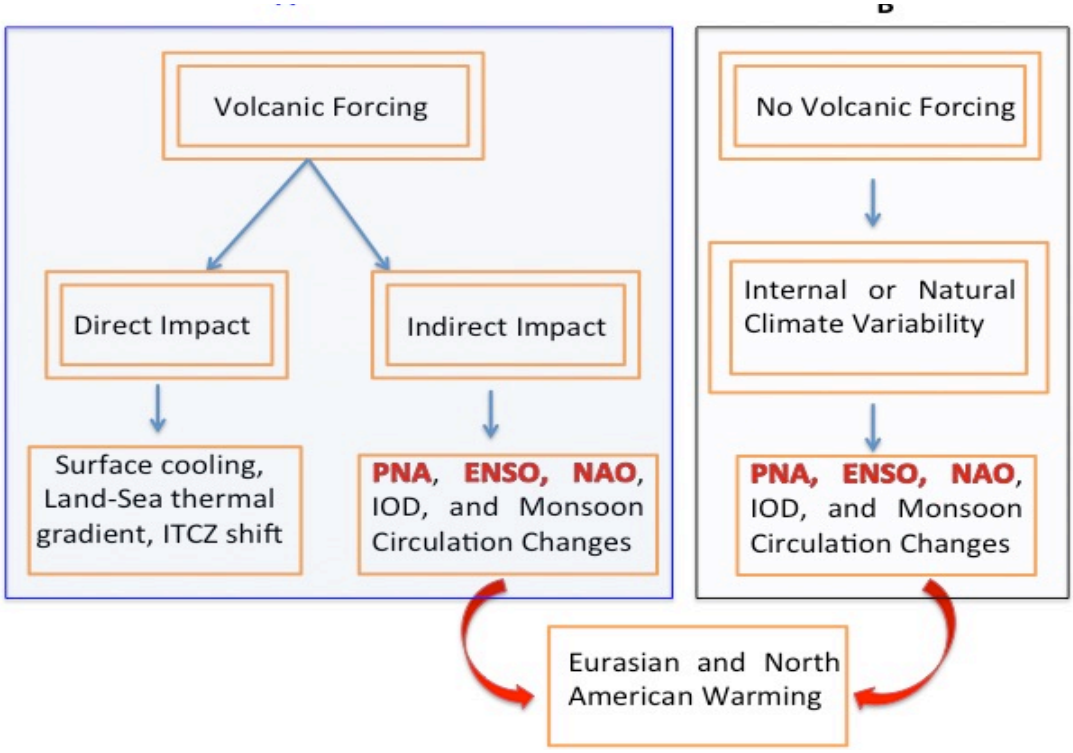

Figure 10: A schematic diagram suggesting two experiments using a large number of coupled GCMs with large ensemble size with volcanic (i.e., panel A) and non-volcanic forcing (i.e., panel B). The difference of the ensemble average of these multi-model, large ensemble volcanic forcing experiments from non-volcanic experiments is required to delineate the volcanic impact (i.e., direct and non-direct) from natural climate variability. Large-scale circulation changes that supposedly play role in high-latitude winter warming are shown in bold red font.