1. Introduction

Strong, explosive volcanic eruptions are an intermittent, natural source of climate variability acting on both inter-annual and decadal scales. Explosive volcanic eruptions eject sulfur dioxide, halogens, ash and water vapor into the stratosphere, where the particles are converted into sulfate aerosols (LeGrande et al., 2016). The loading of stratospheric aerosols increases aerosol optical depth of the atmosphere (Lacis, 2015), thus imposing a radiative forcing via scattering of shortwave radiation and absorption of longwave radiation in the stratosphere (Zanchettin et al., 2013).

The impact that a strong volcanic eruption makes on the climate system depends on many factors including size, ejection height, and location of the eruption. Timing of an eruption also contributes to the climate system's response, with seasonal timing and initial climate conditions at the time of the eruption also influencing the climate response. These factors impact the amount, location and dynamics of how aerosols are loaded in the atmosphere, significantly impacting how the climate system responds to the perturbation (Timmreck et al., 2010; LeGrande and Anchukaitis, 2015). Mt. Pinatubo is an example of one such strong volcanic eruption which erupted in the Philippines in June 1991, ejecting 18 Tg of SO2 into the atmosphere at a height of 20 km (Stenchikov et al., 1998). The Mt. Pinatubo eruption has been widely studied as one of the largest volcanic eruptions in the last decade (McCormick et al., 1995; Bluth et al., 1992; Stenchikov et al., 1998). Climate models are frequently used to study this eruption, as aerosols are relatively well constrained using satellite observations of the eruption

Climate variability such as the El Nino Southern Oscillation System (ENSO) and North Atlantic Oscillation (NAO) continuously cause variations in Earth's climate over time (Philander, 1983; Allan et al., 1996; Timmermann et al., 2018). Climate modelling studies have examined how the initial state of these climate conditions, when combined with volcanic eruptions, impact interannual and decadal scale climate, showing that while radiative forcing impacts remained the same, different initial climate states cause substantial variability in surface atmospheric and oceanic conditions (Zanchettin et al., 2013; Pausata et al., 2020).

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The Volcanic Model Intercomparison Project (VolMIP) is part of the coordinated effort within the Model Intercomparison Project of CMIP6 (Eyring et al., 2016) that seeks to assess which climate responses to volcanic eruptions are robustly simulated in state of the art climate models. VolMIP proposes a set of experiments each aiming to systematically quantify the modelled climate response to specific types of volcanic eruptions under a unified methodology to reduce variability between model studies. The 'volc-pinatubo-full' VolMIP experiment addresses interannual variability in the climate response to large Pinatubo sized volcanic eruptions, including the NH winter mechanisms and ENSO response (Zanchettin et al., 2022).

Here, we use the volc-pinatubo-full VolMIP simulations run in GISS Model E2.1 under varying initial conditions to investigate variability in the annual to interannual climate response. We discuss variations in the modelled climate response under different initial condition groups, different choices of climate anomalies, and under different ensemble member sampling schemes.

We analyze the modelled response to a Mt. Pinatubo sized eruption on Earth in the absence of greenhouse gases to determine the role of initial conditions in the climate response to such a volcanic eruption. We focus on how initial states of ENSO and NAO conditions create variability in the response to a Pinatubo-sized eruption in GISS Model E2.1 through analysis of an expanded set of the VolMIP ensembles presented in Zanchettin et al. (2022). In particular, we investigate how these initial conditions cause changes in the evolution of the ENSO cycle and the northern hemisphere's first post-eruptive winter using a large ensemble of simulations with a) sampling as defined by the VolMIP protocol (Zanchettin et al., 2016) and b) a randomly sampled ensemble of initial climate conditions. We use these ensembles to examine the impact of initial climate conditions and initial climate sampling on the aggregate response of the climate condition to volcanic forcing. We also further discuss the importance of how climate anomalies are calculated, and demonstrate how the choice of climate anomaly when paired with initial climate conditions, can significantly impact the modelled response to volcanic eruptions.

We examine the Pintaubo-sized post-eruptive ENSO response with GISS Model E2.1-G under varying initial conditions of ENSO to determine if the model supports an El Nino like response after volcanic eruptions and or either of the proposed mechanisms.

We also evaluate the robustness of the NH winter response in GISS E2.1-G. Specifically we look at how the modelled response in the northern hemisphere varies in ensembles of different initial conditions, and with different choices of anomalies which include or intentionally exclude internal climate variability.

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2. Add here an adequate section title

2.1 Impact of the Pinatubo eruption on climate

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The impact of a Pinatubo sized eruption on the Earth's climate system is significant; previous work has shown that Pinatubo sized volcanic eruptions decrease radiative flux in the region [40 ◦N-40 ◦S] by around -4.3 W m−2 at their peak aerosol forcing (Minnis et al., 1993), with radiative effects lasting for about two years after the eruption. In comparison, anthropogenic radiative forcing is estimated to have increased global energy budget by 2.3 W m−2 over the industrial period (Myhre et al., 2013), making volcanic forcing a short-lived but substantial source of natural climate variability. The resulting impacts in the climate system, however, last years after volcanic aerosols have been depleted. The direct impacts of volcanic aerosols include cooling of the Earth's surface and warming of the stratosphere (Lacis, 2015). These direct impacts initiate many other changes in the climate system including changes in atmospheric circulation, the hydrological cycle, the cryosphere, and carbon cycle (Zanchettin et al., 2013).

2. 2 ENSO Response

El Nino Southern Oscillation (ENSO) is an important mode of climate variability which oscillates between positive (El Nino), neutral and negative (La Nina) phases at time scales of about 2-7 years in the equatorial Pacific Ocean (Predybaylo et al., 2017). During positive (negative) phases, the equatorial pacific experiences higher (lower) than average sea surface temperature anomalies. These oceanic changes are associated with changes in both regional climate and global climate connections. Both observational (direct and proxy-based) and model-based studies have been used to examine how ENSO responds to large volcanic perturbations. Some proxy-based and several modelling studies suggest that large, tropical volcanic eruptions increase the likelihood of an El Nino like anomaly following the eruption

(Adams et al., 2003; Predybaylo et al., 2017; Khodri et al., 2017). This response is suggested to be particularly robust when the eruption occurs in the Northern Hemisphere due to the eruption shifting the ITCZ southward, thus weakening trade winds in the Tropical Pacific (Pausata et al., 2020). Weakened trade winds then cause El Nino like conditions via the Bjerknes feedback (Bjerknes, 1969).

Research has also focused on understanding the dynamics of the El Nino anomaly. One suggested mechanism is the ocean dynamical thermostat (Clement et al., 1996), a mechanism which is suggested to cause advection of warm water through differential cooling. A second hypothesis for a post-eruptive El Nino anomaly is post-eruptive land cooling over tropical Africa which initiates warming through the perturbation of Walker circulation cells (Khodri et al., 2017). This mechanism was also shown to cause a sustained 7-year El Nino anomalies in response to soot aerosols from simulated global nuclear war (Coupe et al., 2021). Predybaylo et al. (2017) and Zambri et al. (2019) additionally studied the robustness of the simulated El Nino anomaly under varying initial conditions at the time of volcanic eruptions. While Predybaylo et al. (2017) found enhanced El Nino like warming for all Mt.Pinatubo simulations except those where eruptions occurred in La Nina years, Zambri et al. (2019) found a consistent warming of tropical sea surface temperature in the Nino 3.4 region of 0.5-1.0°C in response to the 1783 Laki Eruption in the WACCAM model.

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Despite several studies supporting El Nino like anomalies, still other observational and modelling studies suggest that there is no statistically significant El Nino like response after several large volcanic eruptions (Dee et al., 2020). These studies argue that anomalies found in observational records and model simulations are not statistically significant, and are rather within the range of natural climate variability (Dee et al., 2020).

2.3 Northern Hemisphere Winter Response

The northern hemisphere (NH) experiences a unique response during the first winter after large volcanic eruptions. Many observational (Graf et al., 2007; Christiansen, 2008) and modelling (Timmreck, 2012; Stenchikov et al., 2002) studies have noted a strengthening of the polar vortex the first winter after a large volcanic eruption. This increased polar vortex circulation in the lower stratosphere is closely associated with an enhanced phase of the Arctic Oscillation (AO) and North Atlantic Oscillation (NAO) – two modes of natural climate variability that are separately defined, but closely related in their associated climate impacts including surface temperature patterns (Cohen and Barlow, 2005). Such increased surface temperature patterns have commonly been observed after large volcanic eruptions such as 1991 Mt. Pinatubo (Robock and Mao, 1995; Kelly et al., 1996), and thus the unique signature of increased surface air temperature over Eurasia termed "winter warming" has been analyzed in several volcanic modelling studies.

Modelling studies from previous climate model inter-comparison projects (CMIP) substantiate post-eruptive winter warming. For example (Zambri and Robock, 2016) analyzed an ensemble of CMIP5 simulations finding that most models produce a winter warming signature over the northern hemisphere corresponding with a stronger polar vortex in the lower stratosphere both over historical 1850-2005 simulation period (Zambri and Robock, 2016) and over the last millennium Zambri et al. (2017). Analysis from individual models have also previously supported winter warming corresponding with strengthened polar vortex circulation: for example the NCAR CAM5 AMIP Large Ensemble showed consistent winter warming in response to both the 1982 El Chinchon and 1991 Pinatubo eruptions (Coupe and Robock, 2021). This increase in surface temperature is also seen in both observational and global modelling studies (Robock and Mao, 1992; Graft et al., 1993).

Still other studies call the robustness of this modelled result into question. For example, other analysis of CMIP5 models show variation in the prevalence of this response (Timmreck et al., 2016; Driscoll et al., 2012) suggesting that large numbers of ensembles may be required to see a significant strengthening of the polar vortex (Bittner et al., 2016). One proposed cause for inconsistencies in the winter warming response is that the simulated winter warming response in a model is within the range of internal variability (Polvani et al., 2019) and thus is not a robust response to volcanic eruptions. Other studies such as Driscoll et al. (2012) and Stenchikov et al. (2006) also find no consistent warming in the northern hemisphere, or strengthening of the polar vortex associated with winter warming.

To better understand why a strengthening of the polar vortex circulation occurs, several studies have proposed mechanisms that link volcanic eruptions with changes in atmospheric circulation Robock and Mao (1995); Robock (2000); Stenchikov et al. (2002). Despite proposed mechanisms, however, some studies suggest that the prevalence of this response may depend on aerosol forcing (Toohey et al., 2014), or may be insignificant in comparison to the range of natural variability in climate (Polvani et al., 2019).

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Further climate modelling experiments have thus been designed to capture variability that may occur due to different initial states of the climate system at the time of a modeled volcanic eruption (Zanchettin et al., 2016). Here, we refer to the states of ENSO and NAO at the time of a prescribed volcanic eruption as "initial conditions" as described by the methodology in the Volcanic Model Intercomparison project (VolMIP, (Zanchettin et al., 2016).

The VolMIP community has looked specifically at how these initial conditions can impact the climate response using a multi-model ensemble, finding minor but significant differences in the climate response to volcanic forcing under different initial conditions (Zanchettin et al., 2022).