Mount Pinatubo's effect on the moisture-based drivers of plant productivity

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Abstract

Large volcanic eruptions can significantly affect the state of the climate, including stratospheric sulfate concentrations, surface and top-of-atmosphere radiative fluxes, stratospheric and surface temperature, and regional hydroclimate. The prevalence of higher natural variability in ~~how~~ the regional rainfall ~~responds~~response to ~~the~~ volcanic-induced climate perturbations creates a ~~knowledge~~ gap in our understanding of how eruptions affect ecohydrological conditions and plant productivity. Here, we will explore the understudied store (soil moisture) and flux (evapotranspiration) of water as the short-term ecohydrological control over plant productivity in response to the 1991 eruption of Mt. Pinatubo. We used the NASA's Earth system model for modeling of the ~~1991's~~ Mt. Pinatubo eruption and ~~detection of~~detect the ensuing hydroclimate ~~response~~responses. The model simulates a ~~radiative perturbation of -5 Wm^{-2} and~~ mean surface cooling of ~0.5 °C following the Mt. Pinatubo eruption ~~in 1991~~. The rainfall response is spatially heterogeneous with large temporal variability, yet still shows suppressed rainfall in the northern hemisphere after the eruption. We find that up to 10-15% of land regions show a statistically significant ~~agricultural~~hydroclimate response~~.~~ (wet and dry) as calculated by the Soil Moisture

Deficit Index (SMDI) and Evapotranspiration Deficit Index (ETDI). Results confirm that these ~~higher-order impacts~~impact metrics successfully present a more robust understanding of ~~inferred~~ plant productivity~~ impacts~~. Our results also explain the geographical dependence of various contributing factors to the compound response and their implications for exploring the climate impacts of such episodic forcings.

Introduction

Volcanic eruptions are the most prominent source of sulfate aerosols in the stratosphere and are ~~among the~~ natural drivers of climate variability. Volcanically~~-~~ injected sulfate aerosols in the stratosphere alter the Earth's radiative balance by simultaneously reflecting incoming solar radiation and absorbing outgoing longwave radiation emitted from the Earth's surface (Robock, 2000). The presence of sulfate aerosol for months to years after an eruption and its microphysical transformation in the stratosphere affect the climate system through numerous direct and indirect effects ~~(Barnes and Hofmann, 1997; Brad Adams et al., 2003; Briffa et al., 1998; Deshler et al., 2003; Lambert et al., 1993; LeGrande et al., 2016; LeGrande and Anchukaitis, 2015; Li et al., 2013; Pinto et al., 1989; Santer et al., 2014; Sigl et al., 2015; Singh et al., 2023; Tejedor et al., 2021; Toohey et al., 2019; Zambri et al., 2017; Zambri and Robock, 2016; Zhao et al., 1995).~~

(Barnes and Hofmann, 1997; Briffa et al., 1998; Deshler et al., 2003; Kremser et al., 2016; LeGrande et al., 2016; Marshall et al., 2022; Tejedor et al., 2021; Timmreck, 2012; Toohey et al., 2019). The Mt. Pinatubo eruption (June 1991) remains the largest eruption in the satellite era, and it has been explicitly documented and analyzed for its radiative and climate impacts. Numerous studies based on satellite observations and supported through different modeling efforts estimated that Mt. Pinatubo injected 10-20 Tg of SO_2 at a range of 18-25 km of plume height ~~(Aquila et al., 2012; Bluth et al., 1992; Dhomse et al., 2014; Gao et al., 2023; McGraw et~~

~~al., 2024; Mills et al., 2016; Sheng et al., 2015a, b; Stenchikov et al., 1998)~~(Aquila et al., 2012; Bluth et al., 1992; Dhomse et al., 2014; Gao et al., 2023; Sheng et al., 2015a, b; Stenchikov et al., 1998). The radiative impacts of Mt. Pinatubo's eruption estimate an aerosol optical depth of 0.15 for 550 nm wavelength, with an effective radius in the range of 0.16 to 1 micrometer (µm) and net radiative forcing on the order of 5-6 Wm^{-2} ~~(Lacis et al., 1992; Sato et al., 1993; Stenchikov et al., 1998).~~(Lacis, 2015; Lacis et al., 1992; Sato et al., 1993; Stenchikov et al., 1998). Estimates of the induced surface cooling range between 0.3-0.7 °C; lower stratosphere warming estimates are in the range of 2-3 °C ~~(Bluth et al., 1992; Dutton and Christy, 1992; Hansen et al., 1992; Labitzke and McCormick, 1992; Lacis et al., 1992; McCormick and Veiga, 1992; Minnis et al., 1993; Ramachandran et al., 2000; Stenchikov et al., 1998 Hansen et al., 1993).~~(Dutton and Christy, 1992; Hansen et al., 1992; Labitzke and McCormick, 1992; Lacis et al., 1992; Minnis et al., 1993; Ramachandran et al., 2000; Stenchikov et al., 1998).

In this study, we aim to explore the mechanisms by which the Mt. Pinatubo eruption affected the hydroclimatic conditions and water-based drivers of plant productivity. Agricultural productivity is sensitive to changes in temperature and precipitation (Lobell and Field, 2007; Olesen and Bindi, 2002; Rosenzweig and Parry, 1994). Although much work has been devoted to understanding Mt. Pinatubo's impacts on plant productivity, the literature has been dominated by studies focusing on impacts from changes to the quantity and quality of incoming solar radiation (Farquhar and Roderick, 2003; Gu et al., 2002, 2003; Jones and Cox, 2001; Robock, 2005). Proctor et al. (2018) have estimated a decrease in C4 (maize) and C3 (soy, rice, and wheat) agricultural crop production in response to Mt. Pinatubo driven mainly by changes in incoming radiation. Krakauer and Randerson (2003) evaluated the role of surface cooling in reduced net primary productivity (NPP ~~(Net Primary Productivity~~) using tree ring growth patterns following multiple Mt. Pinatubo-sized eruptions in the last millennium record. Reduced NPP was found in northern mid to high latitudes, while the signal in the lower latitudes and tropics was either ~~not significant~~insignificant or constrained by ~~the~~ other factors. Other studies have further expanded into societal impact research focusing on volcanically induced ~~poor~~changes to harvest and agricultural productivity over different regions (van Dijk et al., 2023; Hao et al., 2020; Huhtamaa and Helama, 2017; Manning et al., 2017; Singh et al., 2023; Toohey et al., 2016).

Similarly, ~~much~~a plenty of work has been devoted to understanding the hydroclimate response to Mt. Pinatubo through changes in atmospheric precipitation (Barnes et al., 2016; Paik et al., 2020; Trenberth and Dai, 2007)~~. Monsoon~~, as the monsoon seasonal rainfall decreases in the season ~~after an~~following the eruption (Colose et al., 2016; Iles et al., 2013; Liu et al., 2016; Singh et al., 2023; Tejedor et al., 2021). It is also shown that volcanic eruptions can alter regional rainfall and hydroclimate in general, which could prominently affect regional plant productivity (Zuo et al., 2019a, b). However, rainfall alone provides an incomplete understanding of the drought conditions relevant ~~for~~to plant productivity; a rainfall deficit could, in principle, be overcome by moisture stored in the soil. Hence, meteorological drought indices (e.g. SPI (McKee et al., 1993) or PDSI (Palmer 1965)) ~~based on rainfall~~ ignore a full water balance approach. Furthermore, meteorological drought indices tend to be designed to evaluate prolonged periods of abnormally dry weather conditions. For instance, PDSI is an indicator of drought with a 9-month horizon ~~(Mullapudi et al., 2023).~~(Mullapudi et al., 2023). Yet, agricultural crops are heterogeneously sensitive to the timing and degree of moisture deficits during particular portions of the crop growth cycle~~; for instance, corn yield can be decreased by as much as 25% for a 10% water deficit during the pollination stage~~ (Hane and Pumphrey, 1984).

Thus, consideration of indices with high temporal frequency can be ~~especially important~~critical when focusing on agriculture.

Soil moisture is the stock of water stored underground and is a primary source ~~for the flux~~ of water flux to the atmosphere and plants through evapotranspiration. ~~Energetically, evaporation~~Evaporation of water from bare surface soil or transpiration of water during photosynthesis in plants from the root zone soils ~~is demanding, using a dominant~~uses a large portion of absorbed solar energy (Trenberth et al., 2009). Plant transpiration is the largest contributor to land evapotranspiration ~~(Nilson and Assmann, 2007; Seneviratne et al., 2010 and references therein). Soil moisture decrease in the root zone establishes an important~~(Dirmeyer et al., 2006; Lawrence et al., 2007; Nilson and Assmann, 2007; Seneviratne et al., 2010). Soil moisture decrease in the root zone establishes an essential control over plant productivity as transpiration is an integral component of photosynthesis (Chen and Coughenour, 2004; Denissen et al., 2022). Multiple studies have established that water supply is the limiting factor for climatic evapotranspiration over tropical and subtropical land areas, while temperature is an important controlling factor in northern mid- and high latitudes ~~(Dong and Dai, 2017 and references therein). However, soil moisture changes in response to Mt. Pinatubo eruption (1991) are largely underreported in the literature~~(Dong and Dai, 2017; Mintz and Walker, 1993; Nemani et al., 2003; Pan et al., 2015). However, soil moisture changes in response to the Mt. Pinatubo eruption (1991) are underreported in the literature, and it is unclear how soil moisture would respond given volcanically forced changes in primary drivers (temperature and precipitation).

Studying a large (10xPinatubo) volcanic eruption, (Frölicher et al., 2011) have shown that the terrestrial carbon pool is sensitive to the regional (in the tropics and sub-tropics) soil-moisture content through the net-ecosystem productivity. Using the geoengineering large ensemble simulations with the CESM model, (Cheng et al., 2019) have analysed the changes in terrestrial hydrological cycle and discussed the future soil-moisture response and its drivers under a geoengineering scenario. To our knowledge, no study has yet investigated multiple indicators of water use with agricultural productivity after a short-duration event like Mt. Pinatubo eruption. Hence, this study looks to explicitly investigate changes in agricultural drought indices from Mt. Pinatubo by considering the store (soil moisture) and flux (evapotranspiration) of water as potential short-term controls over productivity in particular regions. We use NASA's state-of-the-art Earth system model~~ with interactive aerosol chemistry to conduct the simulation experiments consistent with the counterfactual inference of causation approach for the Mt. Pinatubo eruption. The Mt. Pinatubo effect in the model-simulated climate is evaluated through the various pathways of climate impacts, from the primary dependent variables to the higher order responses controlling plant productivity.~~, which incorporates prognostically evolving aerosols, to conduct simulation experiments following the counterfactual inference of causation approach for the Mt. Pinatubo eruption. We assess the impact of the Mt. Pinatubo eruption on the model-simulated climate via multiple pathways, ranging from primary dependent variables to higher-order responses that influence plant productivity. The use of prognostic aerosols enhances the simulations by capturing dynamically consistent feedbacks between the climate response and volcanic aerosols, including aerosol-radiation interactions and stratosphere-troposphere energy flux exchanges (McGraw and Polvani, 2024). Considering the complexity of modeling the terrestrial system, vegetation demographics, and physiological characteristics, we use the soil moisture and evapotranspiration-based agricultural drought indices SMDI (soil moisture deficit index) and ETDI (evapotranspiration deficit index) ~~developed by (Narasimhan and Srinivasan, 2005) to account for agricultural productivity. We~~

~~evaluate short-term (weekly) and long-term (seasonal) scale changes in SMDI and ETDI relative to statistics over longer modern time-period.~~for short-term and long-term scale to account for agricultural productivity. By focusing on soil moisture and evapotranspiration metrics, the major water-based drivers of plant productivity are explored to deepen our understanding of the ~~impacts~~ Mt. Pinatubo ~~had~~impacts on plant productivity.

2.0 Method, Experiment, and Data

2.1 NASA GISS ModelE2.1 (MATRIX): We use the state-of-the-art Earth system model from the NASA (National Aeronautics and Space Administration) Goddard Institute for Space Studies, NASA GISS ModelE2.1 (Bauer et al., 2020; Kelley et al., 2020). NASA GISS ModelE2.1 has an atmospheric horizontal latitude-longitude grid spacing of 2.0x2.5 degrees (at the equator) with 40 vertical levels and a model top ~~of~~at 0.1 hPa. We used the interactive chemistry version MATRIX (Multiconfiguration Aerosol TRacker of mIXing state) aerosol microphysics module (Bauer et al., 2008, 2020), which is based on the Quadrature Method of Moment (QMOM) to predict aerosol particle number, mass, and size distribution for 16 different mixed modes of the aerosol population. New particle formation is represented by Vehkamäki et al. (2002), along with aerosol-phase chemistry, condensational growth, coagulation, and mixing states (Bauer et al., 2013). 16 mixing states with 51 aerosol tracers for sulfate, nitrate, ammonium, aerosol water, black carbon, organic carbon, sea salt, and mineral dust are resolved in this microphysical module (Bauer et al., 2008, 2020). The first indirect effect of aerosols in terms of changes in cloud properties through nucleation is also computed within MATRIX.

The model's ocean component (GISS Ocean v1) ~~of the model~~ has a horizontal resolution of 1x1.25 degrees, with 40 vertical layers. The land component is the Ent Terrestrial Biosphere Model (TBM) (Kim et al., 2015; Kiang 2012) which includes an interactive carbon cycle (Ito et al., 2020), satellite-derived (MODIS-Moderate Resolution Imaging Spectroradiometer) plant functional type, and monthly variation of leaf area index (Gao et al., 2008; Myneni et al., 2002), and tree height (Simard et al., 2011). ~~Interannual variations in the vegetation properties are controlled by rescaling the vegetation fraction (Figure S6) using historical crops and pasture at grid scale to account for land cover and land use changes (Ito et al., 2020; Miller et al., 2020).~~Interannual variations in the vegetation properties are controlled by rescaling the vegetation fractions (Figure S8) using historical crops and pasture at the grid scale to account for land cover and land use changes (Ito et al., 2020; Miller et al., 2021). The land model has two defined tiles for the soil layer: bare and vegetated, and each has six vertical levels to a depth of 3.5 m (11.5 feet) (Rosenzweig and Abramopoulos, 1997). Rooting ~~depth~~depths for different plant functional ~~type~~types are also given by Rosenzweig and Abramopoulos (1997~~)~~), and more than 60% of roots for crop plant functional ~~type~~types are located within 0.6 m (1.96 feet) of soil depth**.** In this version of the model, ~~for~~ the agricultural grid cells, crop plant functional type, and crop calendar are prescribed according to McDermid et al., (2019). Irrigation in the GISS ModelE is implemented using the water irrigation demand data (IWD~~;~~) (Wisser et al., 2010) and irrigation potential calculations based on (Wada et al., 2013) as discussed in (Cook et al., 2020).

2.2 Experiment Design: The MATRIX version of GISS ModelE2.1 with active tracers is three times more computationally expensive than the non-interactive (prescribed pre-calculated aerosol concentration and extinction) version. We extended an equilibrated 1400-yearlong PI control run with non-interactive tracers with an additional 500 years using the MATRIX version with prognostic tracers before starting the 'historical' run. MATRIX includes the tropospheric chemistry scheme that ~~includes~~contains the inorganic (Ox NOx Hox and CO), organic chemistry of CH4, and higher hydrocarbons (Gery et al., 1989; Shindell, 2001; Shindell et al., 2003). The stratospheric chemistry includes bromine, chlorine, and polar stratospheric clouds (Shindell et al., 2006). Dust emission in the model is controlled by ~~the~~ climate variables such as winds and soil moisture at the spatial and temporal scales (Miller et al., 2006). However, anthropogenic dust is not included in GISS ModelE2.1. Other anthropogenic emissions, including biomass burning (pre-1997 from (van Marle et al., 2017) and 1997 onwards from the GFED4s inventory (van der Werf et al., 2017)), are taken from the Community Emission Data System (CEDS) inventory (Hoesly et al., 2018). Most importantly, the volcanic SO_2 forcing for the 'historical' run (1850-1977) is the daily emission rate from VolcanEESM (Neely and Schmidt 2016 : https://catalogue.ceda.ac.uk/uuid/a8a7e52b299a46c9b09d8e56b283d385 ~~) and satellite measurement driven SO_2 inventory (Carn et al., 2017) for 1978 to 2022. The cumulative Mt. Pinatubo emission is 15194 kt (~15.2 Tg) of SO_2 injected from 12^th^~~), and satellite measurement based SO_2 inventory (Carn et al., 2016) for 1978 to 2014 (extended up to 2021). The cumulative Mt. Pinatubo emission is 15194 kt (~15.2 Tg) of SO_2 injected from 13^{th} to 16^{th} of June 1991 above the Mt. Pinatubo vent, with a maximum of 15000 kt (15 Tg) emitted on June 15th at a plume height of 25 km ~~(Diehl~~Carn et al., ~~2012~~(2016). The MATRIX version of the GISS ModelE2.1 used for all of our simulations predicts the nucleation, evolution, and removal of sulfate aerosols prognostically.

The model simulations we performed (Table 1) are described here. We started from the 1400-year-long preindustrial control run from CMIP6 (GISS-CMIP6-PI) with the prescribed average AOD historical period, which is further extended for 500 years using the GISS ModelE2.1 – MATRIX with prognostic tracers (GISS-PI). Then, the CMIP6 historical run (GISS-HIST-SO2; 1850-2014) started with all forcings as specified by CMIP6 except the daily emission rate of injection of SO2 (VolcanEESM) (Carn et al., 2016; Neely III and Schmidt, 2016). We branched out the experiment ensemble with Mt. Pinatubo eruption (GISS-PIN-SO2) and the counterfactual ensemble without Mt. Pinatubo (GISS-NOPIN-SO2) from the historical (GISS-HIST-SO2) using perturbed initial conditions (1st Jan 1986) from the year 1986 to 1999. The perturbation to the initial conditions is generated by altering the radiation-related random number generator that deals with fractional cloudiness in the column.

Table 1: Simulation experiment ~~design~~details.

EXP Name	**Description**	**Time period /run length**	**~~Ensembles~~# of ensembles**	**~~Configuration~~**
GISS-CMIP6-PI	Preindustrial	1850 climatology /~~1300~~1400 years	1	~~GISS ModelE2.1 – MATRIX with prescribed stratospheric aerosols (average volcanic AOD for historical period, 1850-2014)~~
GISS-PI	Preindustrial	1850 climatology /500 years	1	~~Extension to GISS-CMIP6-PI using GISS ModelE2.1 – MATRIX with prognostic tracers~~
GISS-HIST-SO_2	historical	1850-2014 /165 years	1	~~GISS ModelE2.1 – MATRIX with all forcings as specified by CMIP6 except daily emission rate of injection of SO_2 (VolcanEESM; Neely & Schmidt 2016; Carn et al., 2017)~~
GISS-PIN-SO_2	historical	1986-1999 / 15 years	11*	~~GISS ModelE2.1 – MATRIX Branched out from GISS-HIST-SO2, with all forcings as specified by~~

Deleted Cells

				~~CMIP6 except daily emission rate of SO_2 from a combination of VolcanEESM (Neely & Schmidt 2016) and Carn et al., 2017.~~
GISS-NOPIN-SO_2	historical	1986-1999 / 15 years	11*	~~GISS ModelE2.1 – MATRIX with all forcings as according to CMIP6 with daily emission rate of SO_2~~ ~~**without Mt. Pinatubo**~~ ~~from a combination of VolcanEESM (Neely & Schmidt 2016) and Carn et al., 2017.~~

*These ensemble members are branched out from the GISS-HIST-SO_2 by perturbing ~~a radiation-related random number generator that deals with fractional cloudiness in the column~~the initial conditions.

2.3 Methods: This study ~~aims to explore~~investigates the impacts of the Mt. Pinatubo eruption on the major drivers of primary productivity, focusing on soil moisture-related metrics and evapotranspiration. Hereafter, we use the terminology 'PCH' (Mt. Pinatubo and Cerro Hudson) to refer to the 'GISS-PIN-SO2' and 'NP' for the counter-factual ensemble 'GISS-NOPIN-SO2'. ~~Since~~We have included the Cerro Hudson eruption in both ensembles since we are focusing on the Mt. Pinatubo-~~-~~driven climate response~~, we have included the Cerro Hudson eruption in both ensembles~~.

2.3.1 Statistical analysis ~~used to detect~~for detecting Mt. Pinatubo-significant regions and ~~calculate their~~ anomalies calculations.

We treat the no-Pinatubo ensemble (NP) as a counter-factual climate simulation and utilize it to perform the paired Student's t-test. The null hypothesis is that the ensemble means of a quantity of interest (QoI) in a region over a time period are the same between ensembles~~:~~ (i.e. $H_o: \bar{\mu}_{PCH} = \bar{\mu}_{NP}$~~. Regions filled in grey in~~). In the subsequent figures in this document~~,~~, gray regions indicate ~~that~~non-rejection of the null hypothesis ~~cannot be rejected~~ at the 95% confidence level~~. Regions in which the null hypothesis is not accepted are highlighted in color in subsequent plots, where~~, while the ~~color hues~~colored areas highlight its rejection and show anomalies ~~with respect~~relative to ~~the~~1950-2014 simulated climatology (see Supplementary information section S1.0). However, directly comparing the difference between the two ensembles (PCH and NP) is an alternative approach to presenting the Pinatubo effect (see Supplement Figure S2). Using either approach leads to the same general conclusions, with only small quantitative differences. Nevertheless, we chose to remain consistent with the baseline requirements for other metrics as well and used the historical climatology for ~~the~~ period 1950-2014~~.~~ as the baseline for the core of our analysis. The coloring ~~is done to emphasize~~emphasizes the significant regions of anomalies~~, but~~. But we also emphasize the difference in calculations: the grey ~~regions~~areas show no significant change between the PCH and NP ensembles, while the anomalies are PCH ensemble mean minus climatology.

2.4 Impact metrics

The distribution of incoming and outgoing radiation influences the hydrological cycle (Kiehl and Trenberth, 1997; Trenberth and Dai, 2007). A reduction of solar radiation at the surface has the potential to reduce rainfall and change the latent heat-dominated atmospheric heating pattern (Trenberth and Stepaniak, 2004). The perturbed atmospheric conditions and surface energy budget could affect soil moisture. Along with the surface air temperature and precipitation, we use soil moisture and surface energy budget-oriented drought indices (the soil moisture deficit index (SMDI) and evapotranspiration deficit index (ETDI)) to evaluate the land-atmosphere interaction and account for the potential drivers ~~to the crop plant productivity in the model simulated post- Mt. Pinatubo environmental conditions (Narasimhan and Srinivasan 2005). SMDI represents the land-based soil moisture state in selected depth horizons (i.e.~~of the crop plant productivity in the model simulated post- Mt. Pinatubo environmental conditions (Narasimhan and Srinivasan, 2005). SMDI represents the land-based soil moisture state in selected depth horizons (i.e., SMDI_2 means Soil Moisture Deficit Index for 2 feet (0.6 m) depth). ETDI represents the atmospheric conditions governing the land-atmosphere interaction and is also an indicator of plant health. Lastly, plant transpiration is analyzed to the explore the simulated physiological response to the volcanically induced hydroclimatic conditions.

The Palmer drought severity index (PDSI) and other indices are commonly used to represent climatological drought conditions~~, but~~. However, we focus on SMDI and ETDI because these can ~~represent~~capture short-term developing agricultural drought conditions ~~as a response to~~that impact plant productivity and are free from the limitations of other metrics like PDSI. For example, SMDI and ETDI are seasonally independent measures and are comparable across space, even for different climatic zones.

SMDI and ETDI were calculated as described in Narasimhan and Srinivasan (2005) using model output at monthly and daily scales. Daily model output is resampled to a weekly scale to compute the indices. ~~Weekly~~The weekly frequency is used because it is suitable for agricultural applications, and the daily frequency is comparatively higher ~~and~~, which makes these indices computationally expensive ~~for such indices.~~. Below, we reproduce the weekly calculation of SMDI and ETDI as presented in Narasimhan and Srinivasan (2005).

2.4.1 Soil Moisture Deficit ~~Indices~~Index (SMDI) : ~~Soil~~The soil moisture deficit index measures the wetness/dryness of ~~the~~ soil moisture ~~condition~~conditions in comparison to long-~~-~~term records spanning 1950-2014.

$$SD_{i,j} = \frac{SW_{i,j} - MSW_j}{MSW_j - minSW_j} \times 100 \quad \text{if } SW_{i,j} \leq MSW_j \qquad \ldots\ldots (2.4.1a)$$

And

$$SD_{i,j} = \frac{SW_{i,j} - MSW_j}{maxSW_j - MSW_j} \times 100 \quad \text{if } SW_{i,j} > MSW_j \qquad \ldots\ldots (2.4.1b)$$

$SD_{i,j}$ is the soil water deficit (%) for week j of the year i. $SW_{i,j}$ is the mean weekly soil water available in the soil profile (mm) for week j of the year i, MSW_j is the long-term (calibration period) median available water in the soil profile (mm) for week j, and $minSW_j$ and $maxSW_j$ are the j[th] weekly minimum and maximum of soil water available in the soil profile across the calibration period (1950-2014). The soil ~~mositure~~moisture deficit index for any given week can be calculated as

$$SMDI_j = 0.5 * SMDI_{j-1} + SD_j/50 \qquad \ldots\ldots (2.4.1c)$$

SMDI can be calculated for different soil depths ~~of soil~~; we used the 2, 4, and 6-~~-~~feet depths for SMDI estimation, approximately 0.6, 1.2, and 1.8 meters, respectively. For SMDI, it is typical to use feet instead of meters in the literature, which is why we use the same units ~~here.~~along with the coventional SI units in brackets here. SMDI-4 means we considered the soil moisture content between 2 (0.6 m) to 4 feet (1.2 m) in depth. Similarly, SMDI-6 indicates the soil moisture content between 4 (1.2 m) to 6 feet (1.8 m) in depth.

2.4.2 Evapotranspiration Deficit Index (ETDI): The limitations of the Palmer Drought Severity Index (PDSI~~;~~) (Palmer, 1965) and Crop Moisture Index (CMI~~;~~) (Palmer, 1968)~~)~~ in the formulation used for PET ~~calculation (~~Thornthwaite, ~~(~~1948) calculation and lack of accountability to the land cover type on water balance encouraged the exploration of ETDI for agricultural productivity. Also, in the climate models, surface energy fluxes are parameterized in terms of the ~~thermodynamical~~thermodynamic gradient of atmosphere and land models and thus represent the land-atmosphere interactions, which are not accounted for by these atmosphere-only indices. We utilized model simulated surface energy fluxes (Latent and Sensible heat) to calculate the potential (PET) and actual evapotranspiration (AET) to estimate the water stress ratio. However, the applicability of the Penman-Monteith equation for reference crops (Allen et al., ~~(~~1998) provides a substitute method for PET calculation, which~~, although not shown,~~ broadly produced similar results~~.~~ (not shown).

In ~~Equation~~Equations 2.4.2a and 2.4.2b~~.~~, we used the model simulated energy fluxes to calculate AET and PET as suggested in (Milly and Dunne, 2016; Scheff and Frierson, 2015).

The energy budget equation at the surface is given by Rn= G + LH+SH, where Rn is ~~incoming~~net solar radiation, G is net ground ~~energy,~~heating (heat flux), LH and SH represent the Latent and Sensible heat fluxes, respectively. We then use these to calculate PET and AET (unit as mm per day~~):~~; 1 Wm^{-2} = 0.0353 mm/day):

PET = $0.8(R_n - G)$ = (0.8 * 0.~~0864/2.45~~0353) * (LH + SH) ……. (2.4.2a)

And

AET = LH* (0.~~0864/2.45~~0353). ……. (2.4.2b)

The evapotranspiration deficit index is estimated using the water stress condition using the actual evapotranspiration (AET) and potential evapotranspiration (PET) per grid cell, as given below.

$WS = \frac{PET - AET}{PET}$ ….. (2.4.2c)

WS ~~ranges between~~range, from 0 to 1, where 0 signifies that evapotranspiration is happening at the potential rate and 1 ~~stands~~stand for no actual evapotranspiration. WS represents the water stress ratio ~~at~~on a monthly or weekly basis (WS_j), which is further utilized to calculate water stress anomaly ($WSA_{i,j}$) for week j of year i as given below.

$$WSA_{i,j} = \frac{MWS_j - WS_{i,j}}{MWS_j - minWS_j} \times 100 \quad \text{if } WS_{i,j} \leq MWS_j \quad \ldots\ldots (2.4.2d)$$

And

$$WSA_{i,j} = \frac{MWS_j - WS_{i,j}}{maxWS_j - MWS_j} \times 100 \quad \text{if } WS_{i,j} > MWS_j \quad \ldots\ldots\ldots (2.4.2e)$$

Here, MWS_j, $minWS_j$, and $maxWS_j$ represent the ~~longterm~~long-term median, minimum, and maximum of the water stress ratio over the calibration period. Water stress anomaly ranges between -100% to 100%, indicating very dry to wet conditions over the region.

Finally~~ the severity of the~~, drought ~~condition~~severity is calculated as ETDI, similar to SMDI (equation 2.4.1c) at a monthly/weekly time scale.

$ETDI_j = 0.5 * ETDI_{j-1} + WSA_j / 50$. ……... (2.4.2f)

The indices SMDI and ETDI range from -4 to +4, representing the excessive wet and dry conditions. The bounding values -4 or +4 represent extremely dry/wet conditions as the deficit/excess of soil-moisture deficit (SM) or water stress anomaly (WSA) ~~is~~ reached, relative to the maximum over the reference calibration period.

We also highlight the justification for selecting 1950-2014 as the base period for analyzing the response in climate variables and the long-term calibration period for drought indices calculations. (Supplementary information section ~~1s~~S1).

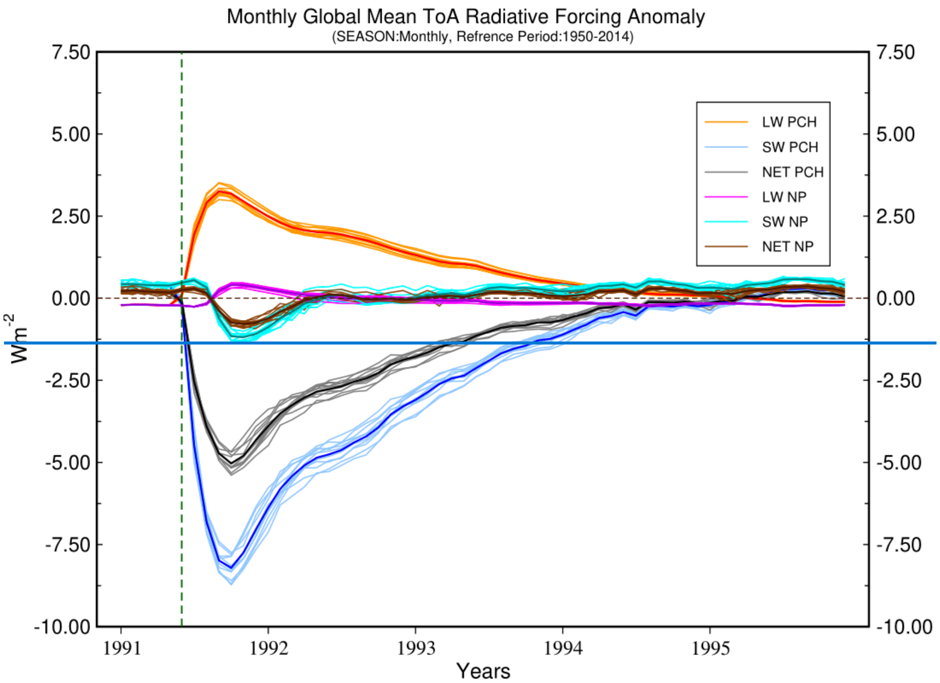
3.0 Results

The result section of this study first presents the NASA GISS model's simulated properties of the 1991 Mt. Pinatubo eruption, and then further ~~evaluates~~the evaluation of the primary (aerosol optical depth, radiation, and temperature) and secondary (precipitation, soil moisture, evapotranspiration, and transpiration) impacts on plant productivity.

3.1 Radiative ~~forcings and~~forcing response

~~We analyze the microphysical and radiative properties of volcanic aerosol simulated by the NASA GISS ModelE (MATRIX) in the PCH ensemble set. The current setup of GISS ModelE uses the aerosol microphysical module MATRIX represent the various states and provide particle number, mass, and size information for different mixed modes of the aerosol population. In the simulation of the Mt. Pinatubo eruption~~In the Mt. Pinatubo eruption simulation, the volcanically injected SO_2 in the stratosphere oxidizes in the presence of prognostically evolving OH radicals to form the stratospheric sulfate aerosols~~. Sulfate aerosols grow by condensation of gas (nucleation, and self-coagulation (preexisting)) to the Aitken (AKK) mode (mean mass diameter <0.1 µm), and further growth in size leads to the transfer to Accumulation (ACC) mode (Bauer et al., 2008; Bekki, 1995). The transfer between the two particle modes is controlled through the transfer function based on particle mean mass diameter (Bauer et al., 2008). GISS ModelE (MATRIX) PCH simulated a sulfate aerosol size with an effective radius (R_{eff}) of the order of 0.3-0.6 µm after the Mt. Pinatubo eruption (not shown), consistent with several observation and modeling estimates (Bauman et al., 2003; Bingen et al., 2004; Russell et al., 1996; Stenchikov et al., 1998). GISS ModelE (MATRIX) PCH simulated a peak global mean aerosol optical depth (AOD; for 550 nm wavelength) of 0.21 (Supplementary Fig S2 bottom panel) a few months after the eruption, which then decreases due to deposition~~ (Supplementary section S2.0). GISS ModelE (MATRIX) PCH also simulated a peak global mean aerosol optical depth (AOD; for 550 nm wavelength) of 0.22 (Supplementary Fig S4 bottom panel) a few months after the eruption, which then decreases with time due to the deposition of volcanic aerosols (English et al., 2013; Sato et al., 1993). ~~Here~~In this study, the model-simulated ~~extinction of the radiation~~aerosol optical depth (AOD) due to volcanic aerosol and radiative forcing is larger than the previously reported AOD of 0.15 and forcing of -4.0 to -5.0 Wm^{-2} due to the Mt. Pinatubo eruption (Hansen et al., 1992; Lacis et al., 1992).

The mass and size of volcanic sulfate aerosol firmly control the scattering of the incoming shortwave radiation and the absorption of longwave ~~(Brown et al., 2024; Kinne et al., 1992; Lacis, 2015; Lacis et al., 1992; Lacis and Hansen, 1974)~~(Kinne et al., 1992; Lacis, 2015; Lacis et al., 1992; Lacis and Hansen, 1974). ~~The first-order climate response to the volcanically-injected sulfate aerosol in the stratosphere is the perturbation of the radiative balance of the Earth system (Hansen et al., 1980; Lacis et al., 1992; Stenchikov et al., 1998). Figure 1~~The first-order climate response to the volcanically-injected sulfate aerosol in the stratosphere is the perturbation of the radiative balance of the Earth system (Brown et al., 2024; Hansen et al., 1980; Lacis et al., 1992; Stenchikov et al., 1998). Supplementary figure S3 shows that the GISS ModelE PCH has simulated a peak longwave, shortwave, and net radiative response of +3.0 Wm^{-2}, -8.0 Wm^{-2}, and -5.0 Wm^{-2} respectively, a few months after the eruption, which recovers slowly in next 24 months and is consistent with previous studies (Stenchikov et al., 1998; Hansen et al., 1992; Minnis et al., 1993; Brown et al., 2024). ~~These radiative responses are calculated with respect to the climatology for the period 1950-2014 in GISS-Hist-SO2.~~ The GISS model also simulated a smaller peak ranging within -1 Wm^{-2} in the counterfactual (without Mt. Pinatubo) runs, likely due to the Cerro Hudson eruption in August 1991.



~~Figure 1. Monthly anomaly of longwave, shortwave, and net radiative forcing simulated by the GISS ModelE for Mt. Pinatubo (PCH) and counterfactual (NP) ensemble. The response anomalies are calculated with respect the climatology for the period 1950-2014, taken from the GISS historical runs (GISS-HIST-SO2). The light-colored thin lines represent the individual ensemble member, and the dark broad line is multi-ensemble mean for each variable (longwave, shortwave and net radiative response).~~

3.2 Aerosol dispersion and ~~Temperature Response~~temperature response

~~Figure 2 shows the zonal mean anomaly for the aerosol optical depth (AOD), lower stratosphere temperature (MSU-TLS satellite simulator), and surface temperature. The zonal AOD shows the dispersion and transport of aerosol poleward after the eruption. Horizontal dispersion and transport of the aerosols is strictly influenced by the stratospheric meteorology and atmospheric circulation, which is independent in each ensemble member, and depends on the~~

plume height and season. GISS ModelE has simulated AOD consistently with previous studies (Aquila et al., 2012; Brown et al., 2024; Rogers et al., 1998; Timmreck et al., 1999; Trepte et al., 1993). Cross-equatorial dispersion to the southern hemisphere might be due to the more robust Brewer-Dobson circulation in the austral winter (Aquila et al., 2012). Meanwhile, the phases of QBO and local heating also play a crucial role in the poleward and vertical dispersion of stratospheric aerosols (Hitchman et al., 1994; Ehrmann et al., 2024 (in-prep)). A smaller peak in the southern hemisphere (45° S) in later 1991 likely due to the Cerro Hudson eruption, which injected ~1.5 Tg of SO_2 at a height of 15 km.

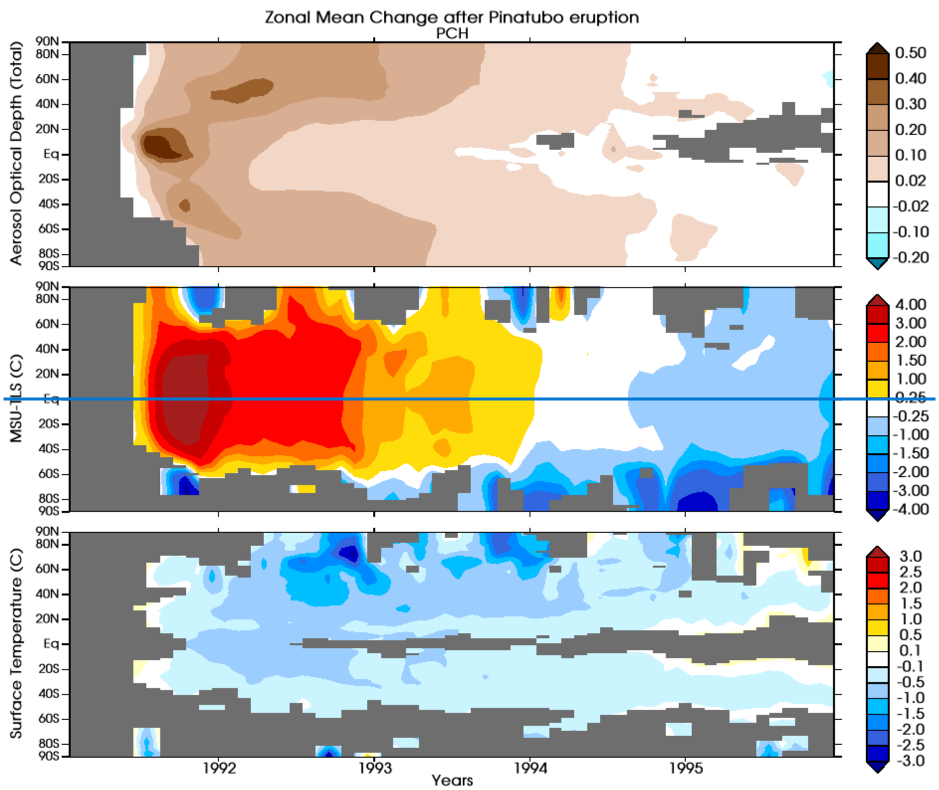


Figure 2. Zonal mean of monthly anomalies for multi ensemble mean for aerosol optical depth at 550 nm (top panel), microwave sounding unit temperature (MSU-TLS) for lower stratosphere (middle panel) and surface air temperature with respect to the 1950-2014 climatology. Gray regions show no statistically significant difference between the PCH and NP responseFigure 1 shows the zonal mean anomaly for the aerosol optical depth (AOD) and surface air temperature. The zonal AOD shows the dispersion and transport of aerosol poleward after the eruption. Horizontal dispersion and transport of the aerosols are strictly influenced by the stratospheric meteorology and atmospheric circulation, which is independent in each ensemble member, and depends on the plume height and season. GISS ModelE has simulated AOD consistently with previous studies (Aquila et al., 2012; Rogers et al., 1998; Timmreck et al., 1999; Trepte et al., 1993). Cross-equatorial dispersion to the southern hemisphere might be due to the more robust Brewer-Dobson circulation in the austral winter (Aquila et al., 2012). Meanwhile, the phases of QBO and local heating also play a crucial role in the poleward and vertical dispersion of stratospheric aerosols (Hitchman et al., 1994). A smaller peak in the southern hemisphere (45° S) in the late 1991, likely due to the Cerro Hudson eruption, which injected ~1.5 Tg of SO_2 at a height of 15 km.

The lower panels in Figure 1 show the surface air. The colored areas show anomalies of PCH with respect to the climatology from 1950-2014.

The middle and lower panels in Figure 2 show the model-simulated microwave sounding unit (MSU) temperature for the tropical lower stratosphere (TLS) response due to absorption of longwave radiation and for the surface temperature response due to the net radiative perturbation, which is dominated by the scattering of incoming solar radiation. The model simulates a peak warming of over 4 °C in the tropical lower stratosphere shortly after the eruption, which lasts for

~~a few months when the concentration of sulfate aerosols is highest. Significant warming in the range 2-3 °C lasts until the end of 1992, and overall simulated stratospheric warming is consistent with previous studies. Figure S2 (top panel) shows a steplike transition with time with a global mean increase of 3.0 °C in the lower stratosphere temperature after the Mt. Pinatubo eruption followed by a trend consistent with Ramaswamy et al., (2006).~~ The zonal structure of surface temperature shows that the surface cooling follows the aerosol optical depth pattern, and the ~~greatest~~most significant cooling is simulated in the northern hemisphere high latitudes. Temporal characteristics of lower stratosphere warming, and surface cooling also show the seasonal variations in incoming solar radiation in northern polar latitudes. Model simulated the lower stratospheric warming due to longwave radiation absorption in lower stratosphere consistent with previous studies (Supplementary text section S3.0).

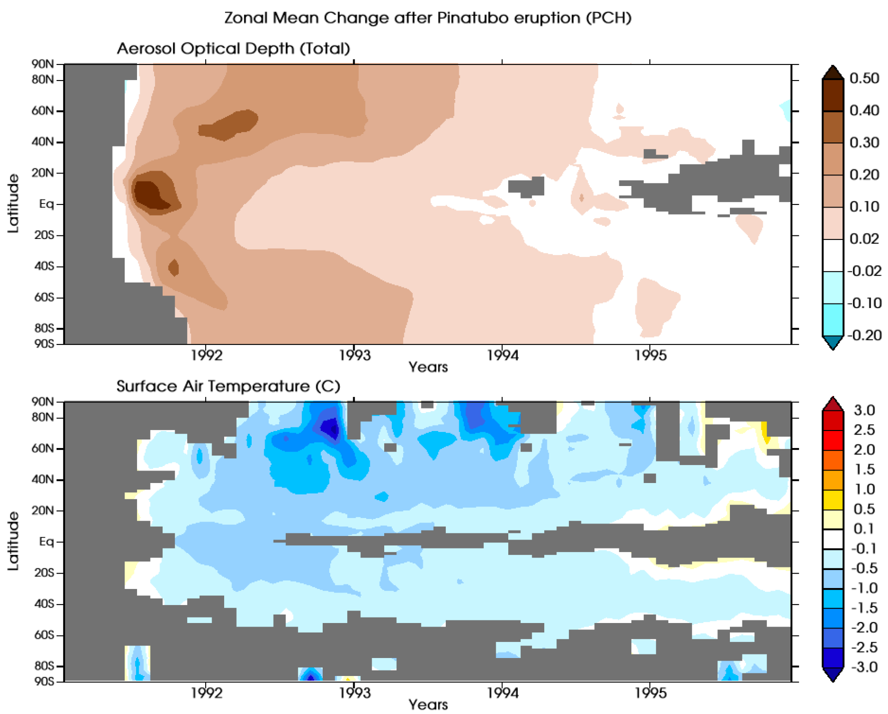


Figure 1. Zonal mean of monthly anomalies for multi-ensemble means for aerosol optical depth at 550 nm (upper panel) and surface air temperature (lower panel) with respect to the 1950-2014 climatology. Gray regions show no statistically significant difference between the PCH and NP responses. The colored areas show anomalies of PCH with respect to the climatology from 1950-2014. ~~of sunlight in northern polar latitudes.~~

The spatial pattern of surface air temperature response is evaluated at the seasonal scale for each year from 1991 to 1995 ~~as shown in Figure 3. We conclude that the volcanic forcing from the Mt. Pinatubo eruption results in a statistically different seasonal mean surface air temperature response. Figure 3 shows that a spatial pattern of surface cooling starts appearing after a few months of the eruption (during the SON season of the year 1991) when the gaseous~~

~~SO_2 is oxidized into sulfate aerosols. The surface cooling signature due to the volcanic aerosols is significant in 1992 and 1993 before recovering in 1994 towards pre-eruption temperature conditions. The highest surface cooling is noticed over the sub-tropics and higher latitude land regions in the northern hemisphere and reaches up to 2.5 °C at a regional scale.~~, as shown in Figure 2. We conclude that the volcanic forcing from the Mt. Pinatubo eruption results in a detectable seasonal mean surface air temperature response. Figure 2 shows that a spatial pattern of surface cooling starts appearing after a few months of the eruption (during the SON season of 1991) when the gaseous SO_2 is oxidized into sulfate aerosols. The surface cooling signature due to the volcanic aerosols was significant in 1992 and 1993 before recovering in 1994 towards pre-eruption temperature conditions. The highest surface cooling is noticed over the sub-tropics and higher latitude land regions in the northern hemisphere and reaches up to 2.5 °C at a regional scale. To summarize: the PCH GISS ModelE simulated global mean peak cooling response is ~0.5 °C after the eruption, as shown in Supplement Figure S4 (Middle panel), with a range between 0.25 – 1.0 °C for individual ensemble members, and this is consistent with the various observation and modeling studies (Dutton and Christy, 1992; Hansen et al., 1996; Kirchner et al., 1999; Minnis et al., 1993; Parker et al., 1996; Ramachandran et al., 2000; Stenchikov et al., 1998).

~~To summarize: the PCH GISS ModelE simulated global mean peak cooling response is ~0.5 °C after the eruption as shown in Supplement figure S2 (Middle panel) with a range between 0.25 – 1.0 °C for individual ensemble members, and this is consistent with the various observation and modeling studies (Brown et al., 2024; Dutton and Christy, 1992; Hansen et al., 1996; Minnis et al., 1993; Parker et al., 1996; Ramachandran et al., 2000; Stenchikov et al., 1998)(Kirchner et al., 1999).~~

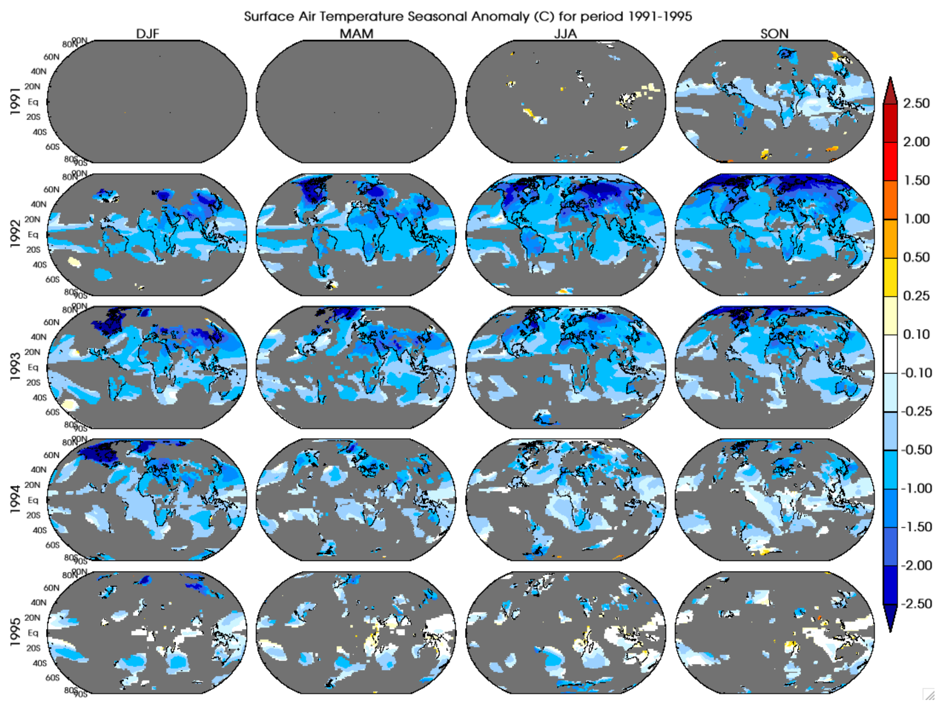


Figure ~~3~~2: Seasonal mean surface temperature anomalies (°C) from the year 1991 to 1995 with respect to the reference period of 1950-2014. A grey color is painted over the grid cells where the surface temperature anomalies are not statistically significant in comparison to the ~~counter-factual~~counterfactual ensemble. The colored areas show anomalies of PCH with respect to the climatology from 1950-2014.

3.3 Rainfall Response

Precipitation, presented seasonally for the year of eruption (1991) and the following year (1992) in Figure ~~4~~3, shows a highly complex and variable response to the volcanically induced tropospheric cooling and radiative balance perturbation because of its sensitivity to the other climate system components. Studies have shown that global mean precipitation decreases after large volcanic eruptions (Gu et al., 2007; Gu and Adler, 2012; Iles et al., 2013; Robock and Liu, 1994; Singh et al., 2023; Trenberth and Dai, 2007). Colose et al., (2016) have postulated that the asymmetrical surface cooling and radiative balance perturbation create an energetic deficit in the hemisphere of eruption that constrains the poleward propagation of tropical rainfall belt (ITCZ) in that hemisphere. In the case of the Mt. Pinatubo eruption, the PCH simulations show that regional patches of significant decrease of up to 1 mm per day are ~~spotted~~noticed over tropical and northern hemispheres (Africa, eastern and northern Asia) after the eruption (Figure ~~4~~3). Also, increasing rainfall patterns are simulated over the Mediterranean and European regions. Broadly, the confidence level of precipitation response due to volcanic aerosols is strongly influenced by the uncertainty due to many possible factors and prominent modes of atmospheric variability, such as the strength of El Nino (Paik et al., 2020).

The zonal mean of the rainfall response (Figure ~~S3~~S5) shows a clear decreasing trend in the northern hemisphere tropical and higher latitudes with a positive rainfall response band around 20° N. The PCH modelled rainfall response due to the Mt. Pinatubo eruption is broadly consistent with the previous studies (Joseph and Zeng, 2011; Liu et al., 2016; Trenberth and Dai, 2007), but the uncertainty in rainfall response is still high. Although we use statistical significance at 95% confidence level as our metric ~~of~~for determining significant anomalies~~, we do not deny erroneous~~ and only a few regions exhibit a spatially coherent and detectable forced response (Figure 3). We acknowledge the signals due to the model's internal variability when averaging the impacts across multiple ensembles ~~(Polvani et al., 2019). The inconsistency and complexity in the precipitation response drives us to explore the compound hydroclimatic pathways of impacts beyond the rainfall such as droughts~~, but 11 ensembles are a good compromise between few vs. many ensemble members which was shown to be sufficient to represent significance in climate response at the regional scale (Polvani et al., 2019; Singh and AchutaRao, 2019). The inconsistency and complexity in the precipitation response drive us to explore the compound hydroclimatic pathways that lead to drought risk.

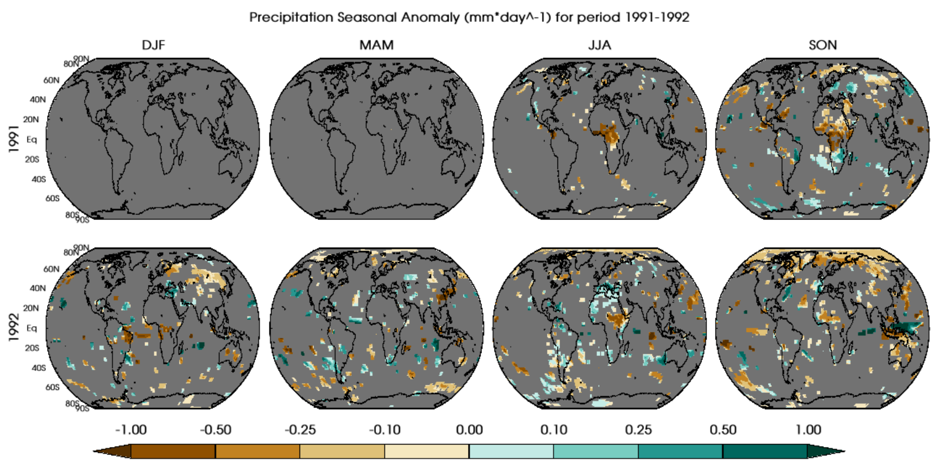


Figure ~~4~~3. Seasonal mean precipitation anomalies (mm per day) from the year 1991 and 1992 with respect to the reference period of 1950-2014. A grey color is painted over the grid cells where the precipitation anomalies are not statistically significant in comparison to the ~~counter-factual~~counterfactual ensemble. The colored areas show anomalies of PCH with respect to the climatology from 1950-2014.

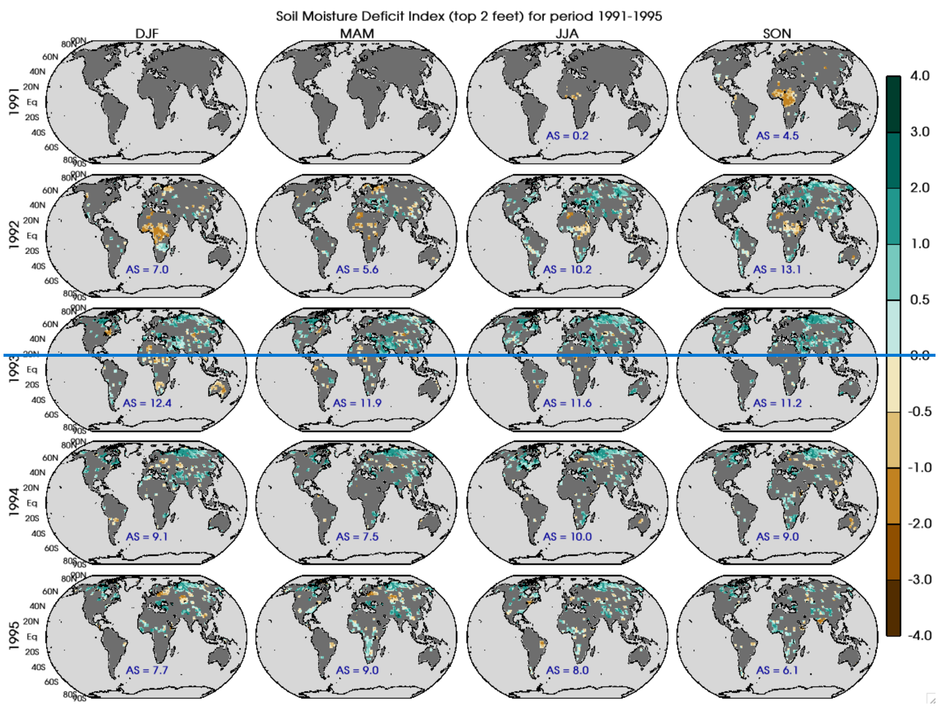
3.4 Drought Conditions

Land-atmosphere ~~interaction~~interactions under a radiatively perturbed environment ~~plays a~~are crucial ~~role~~ in regulating the climate response at regional and sub-regional scales. ~~Changes in land-atmosphere interactions on~~On short timescales, changes in these interactions can strongly affect plant productivity. Even short-lived adverse conditions in the growth cycle have the potential for outsized impacts, especially if they happen at a particular time in the growing cycle.

Hence, we explore the weekly aspects of these drought conditions in Section ~~4~~3.6 to explore the temporal characteristics of variability in the conditions.

3.4.1 Seasonal Soil Moisture Drought Index (SMDI)

The root zone is commonly defined as the top 3 – 6 feet (0.9-1.8 m) of the soil column ~~(Keshavarz et al., 2014, and references therein)~~(Keshavarz et al., 2014) but most agricultural crops have shallower root systems confined to the top 2 feet (0.6 m) (Narasimhan and Srinivasan 2005). Hence, we focus on the soil moisture deficit index (SMDI) (Narasimhan and Srinivasan 2005) for the top 2 feet (0.6 m) of ground depth (SMDI_2) as shown in Figure ~~5~~4. As anticipated, more land area is covered by statistically different SMDI_2 ~~then~~than in Figure 4 ~~helping to further~~3. This enhances our analysis of water-driven ~~impact to~~impacts on plant productivity ~~more then with~~, offering greater insights than precipitation.


Soil Moisture Deficit Index (top 2 feet) for period 1991-1995
DJF
MAM
JJA
SON
1991
1992
1993
1994
1995
AS = 0.2
AS = 4.5
AS = 7.0
AS = 5.6
AS = 10.2
AS = 13.1
AS = 12.4
AS = 11.9
AS = 11.6
AS = 11.2
AS = 9.1
AS = 7.5
AS = 10.0
AS = 9.0
AS = 7.7
AS = 9.0
AS = 8.0
AS = 6.1
4.0
3.0
2.0
1.0
0.5
0.0
-0.5
-1.0
-2.0
-3.0
-4.0

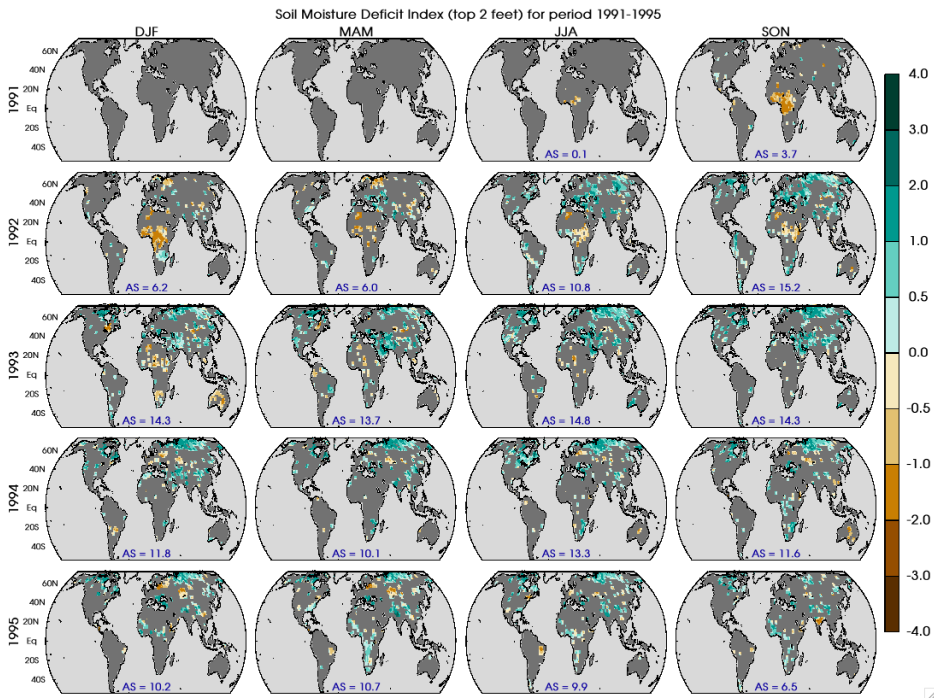


Figure 54. Soil moisture deficit index (SMDI_2) for the top 2 feet(0.6 m) of ground depth evaluated seasonally from 1991 to 1995. Grey color is painted over the grid cell where the SMDI_2 is not statistically significant in contrast to counter-factual ensemble. The parameter AS on each panel markmarks the percentage of land area whichthat has shown statistically significant dry or wet response after Mt. Pinatubo eruption.

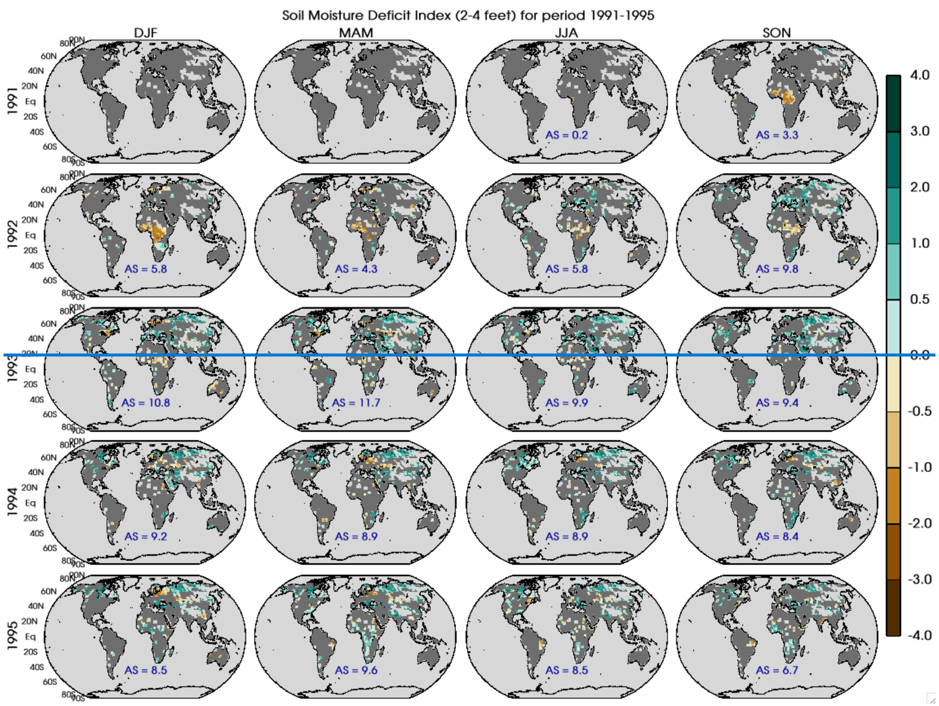
Figure 54 clearly shows that the equatorial region, especially over Africa, has a significant drying response due to Mt. Pinatubo in comparisoncompared to long--term historical data starting from the SON season of 1991 through the following DJF season. Although less robust, the dryness in this region lasted through MAM of 1993. SeverityThe severity of drying response reaches up to -2.0 on a scale of extreme wet/dry at 4.0/-4.0, where athe severity of – 4.0 reflects the maximum dryness (rarest case) over the entire 1950-2014 calibration period. Figure 43 shows a similar pattern in equatorial African rainfall decrease. DecreaseA decrease in rainfall was present in the first season post~~-~~ Mt. Pinatubo eruption, indicating an expected lagged response in SMDI_2.~~-~~ Spatial coherence between these signals is again re-established in the JJA and SON 1992 seasons, albeit with more variation in the strength of the signal.

Meanwhile, in the high latitudes of the northern hemisphere, we see an increase in the store of soil moisture despite a decrease in rainfall in higher latitudes.~~-~~ An exception ~~to this~~ is the Mediterranean (extending towards the east Mediterranean and western ~~Asian~~Asia) region, where soil moisture and rainfall~~,~~ both show an increase ~~during post-~~after the Mt. Pinatubo ~~period~~eruption. This increase in ~~the~~ soil moisture in the northern hemisphere is comparatively more pronounced in the summer months than in ~~comparison to~~ the winter ~~seasons~~season. Thus, despite less water supply through rainfall, there ~~is~~has been a persistent increase in the soil-moisture in the root zone layer ~~starting from~~since the JJA season of 1992. This is likely due to less water extracted from this layer through evaporation and transpiration as well as due to the implemented irrigation in GISS modelE (details in further sections).

Overall, Figure ~~5~~4 shows equatorial drying signals mostly dominated through the DJF season of ~~the year~~ 1993, but the wet conditions over higher latitudes lasted till 1995. Broadly, 6-13% of the land region has shown a statistically significance response in terms of dry/wet ~~condition~~conditions by the end of year 1995 because of the Mt. Pinatubo forcing.

Deeper soil layers better approximate longer-term meteorologically defined drought indices ~~better~~ (Narasimhan and Srinivasan 2005).~~-~~ This makes intuitive sense:~~-~~ precipitation provides the recharge for the store of soil moisture, and if there is a longer-term decline in precipitation, all ~~hydraulically~~ available moisture will be used hydraulically for plant transpiration (both the deeper stores of water and the soil-penetrating precipitation available~~)~~), not allowing for deeper depth recharge.~~-~~ Here, we evaluate discrete layer depths instead of cumulative depths for two reasons.~~ ~~ First, the soil permeability changes with the depth, and the inclusion of top layers erroneously reflects the SMDI_2 signal in potentially impermeable regions; second, the SMDI_2 signal gets superposed over the deeper layer response and misleads the actual soil moisture response for the deeper layers.

As expected, when we evaluate the soil moisture deficit response between 2-4 feet (0.6-1.2 m) soil depth (SMDI_4) in Figure ~~6,~~5 and 4-6-feet (1.2-1.8 m) soil depth (SMDI_6) in Figure ~~S4~~S6, we see similar spatial and temporal distributions as shown in Figure ~~5~~4 with a corresponding decrease in the percentage of area response.~~ ~~ Spatially, we see high latitudes across North America and Northeastern and western Asia, equatorial Africa, ~~European~~Europe, and Mediterranean regions maintain their SMDI-2 trend in Figure ~~5~~4. However, the total ~~area of~~ response area decreases from peak coverages of 12-13% in SMDI-2 to less than 10-12% in SMDI-4 and 7-10% in SMDI_6 (as shown in Figure ~~S4~~S6). Additional decreases in the degree of ~~impacts~~impact are also seen between the three soil layers. Note that the light grey colored regions in Figures ~~6~~5 and ~~S4~~S6 represent regions of impermeability, which does affect the total area of response.


Soil Moisture Deficit Index (2-4 feet) for period 1991-1995
DJF
MAM
JJA
SON
1991
1992
1993
1994
1995
AS = 0.2
AS = 3.3
AS = 5.8
AS = 4.3
AS = 5.8
AS = 9.8
AS = 10.8
AS = 11.7
AS = 9.9
AS = 9.4
AS = 9.2
AS = 8.9
AS = 8.9
AS = 8.4
AS = 8.5
AS = 9.6
AS = 8.5
AS = 6.7
4.0
3.0
2.0
1.0
0.5
0.0
-0.5
-1.0
-2.0
-3.0
-4.0

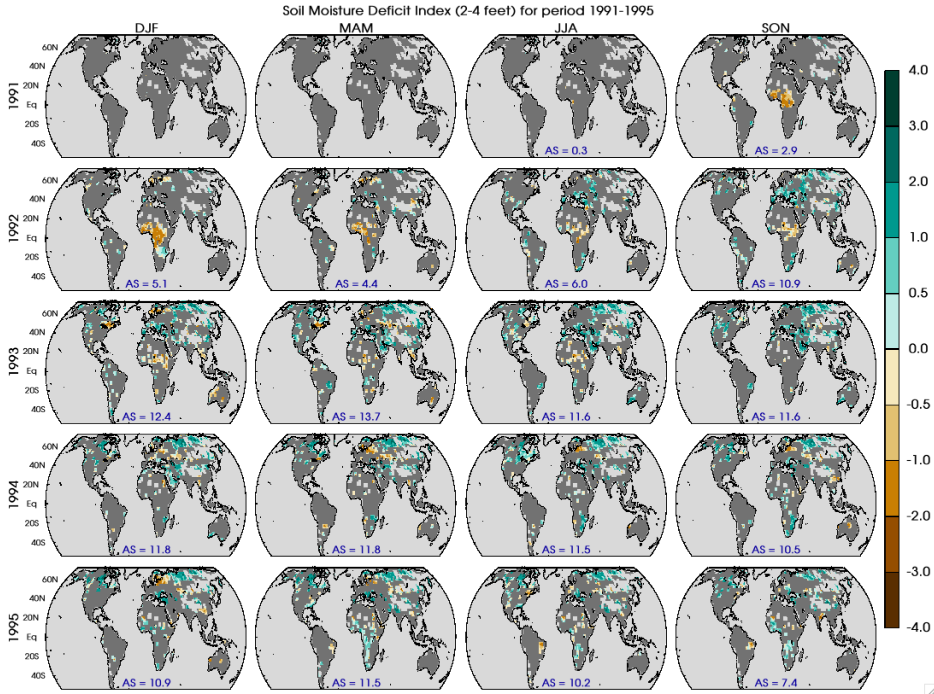
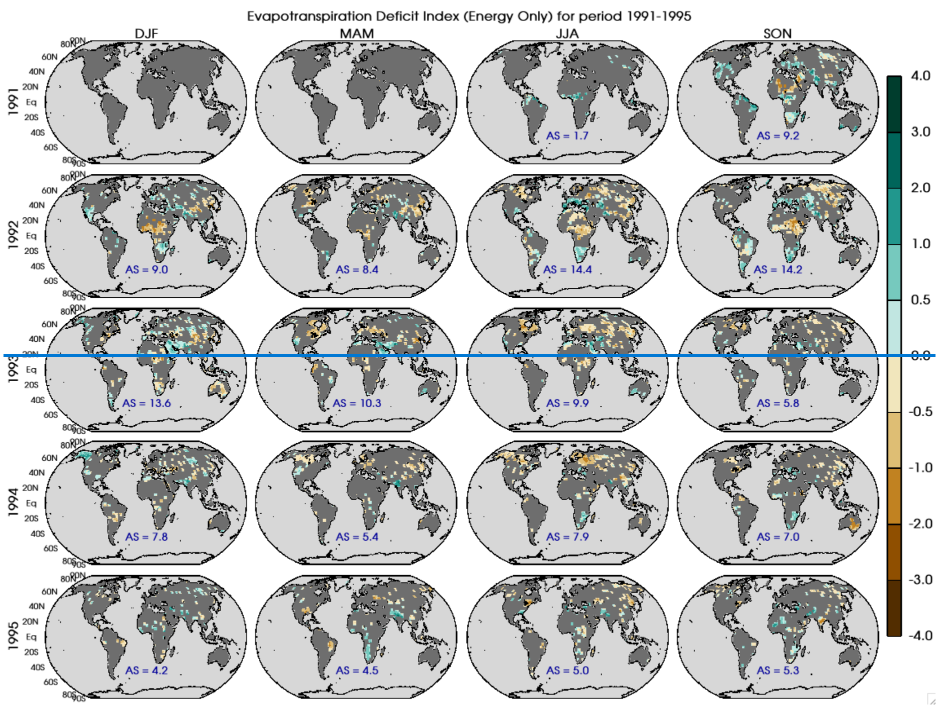


Figure ~~6~~5. Soil moisture deficit index (SMDI_4) for soil depths between 2-4 feet (0.6-1.2 meter) evaluated seasonally from 1991 to 1995. ~~Grey~~The grey color is painted over the grid cell where the SMDI_4 is not statistically significant in contrast to ~~counter-factual~~the counterfactual ensemble. The light grey colored regions represent regions of impermeability. The parameter AS on each panel ~~mark~~marks the percentage of land area ~~which has shown~~showing statistically significant dry or wet response after the Mt. Pinatubo eruption.

3.4.2 Seasonal Evapotranspiration Deficit Index (ETDI)

As indicated in the methodology section, ETDI calculation is similar to SMDI but is based on the water stress anomaly, which accounts for the difference between actual and potential evapotranspiration. ~~This~~ETDI is a measure of the flux of water between land and atmosphere, and like SMDI_2 in Figure ~~6~~5, it shows robust statistical ~~difference~~differences over land.

Figure ~~7 shows that~~6 illustrates the reduction in ETDI response in the equatorial ~~decreases in ETDI~~ region started developing ~~in~~during the DJF season ~~for~~of the year 1992, and these conditions ~~were persistent~~persisted over the year. ~~Similar to~~Like SMDI_2, ETDI increases over the ~~region~~regions encompassing the Mediterranean and western Asia. However, ETDI differs from the SMDI_2 over some ~~of the~~ northern hemisphere regions, especially ~~over~~ Northeastern Asia. A drying response in terms of ETDI in the northern hemisphere regions persisted during 1993 and 1994, whereas SMDI_2 shows an opposite response. This contrasting response ~~in terms of~~ through the ETDI and SMDI_2 points to the complexity of land-atmosphere interactions over these regions. We utilized model simulated surface energy fluxes (Latent and Sensible heat) to calculate the potential (PET) and actual evapotranspiration (AET) to estimate the water stress ratio. In these regions ~~where~~, soil moisture is available ~~in~~during the summer and early winter months~~, but a deficit in~~. Still, an evapotranspiration deficit reflects the decrease in plant transpiration (latent heat flux), which may be due to the unavailability of plants. Also, the surface temperature (sensible heat flux) response supports the non-water-stressed atmospheric conditions, and thus, overall, it ~~show a deficit in~~shows an evapotranspiration deficit. Areas of significant response in terms of ETDI ~~varies~~vary from 7 to 14.5% on a seasonal basis during the years following the eruption. The ~~largest~~most significant areas of ETDI coverage occur during the same ~~time~~ periods as SMDI_2 (between JJA 1992 – JJA 1993).


Evapotranspiration Deficit Index (Energy Only) for period 1991-1995
DJF
MAM
JJA
SON
1991
1992
1993
1994
1995
80N
60N
40N
20N
Eq
20S
40S
60S
80S
AS = 1.7
AS = 9.2
AS = 9.0
AS = 8.4
AS = 14.4
AS = 14.2
AS = 13.6
AS = 10.3
AS = 9.9
AS = 5.8
AS = 7.8
AS = 5.4
AS = 7.9
AS = 7.0
AS = 4.2
AS = 4.5
AS = 5.0
AS = 5.3
4.0
3.0
2.0
1.0
0.5
0.0
-0.5
-1.0
-2.0
-3.0
-4.0

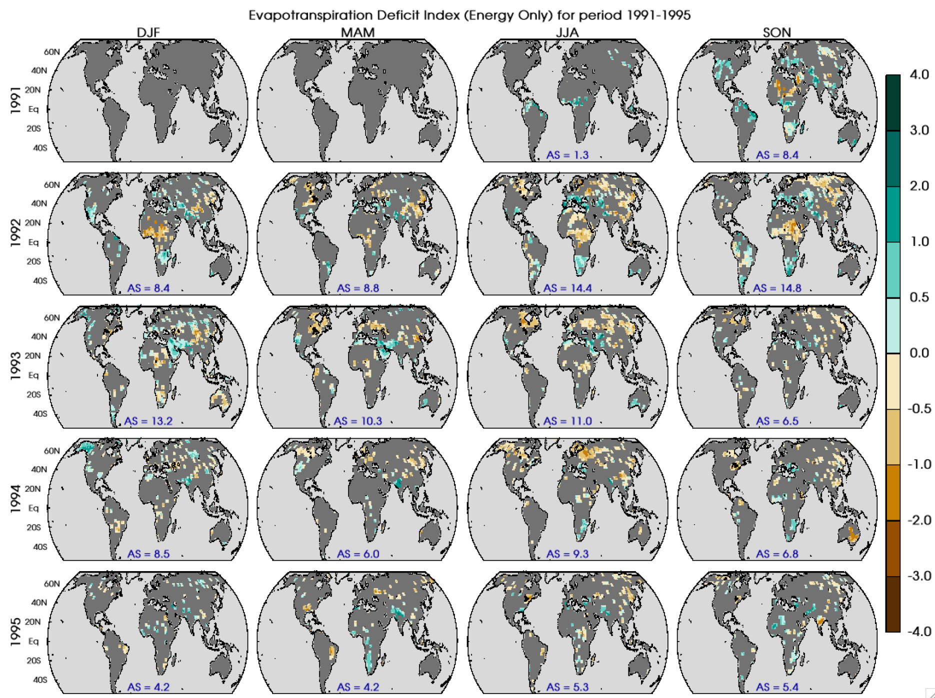


Figure ~~7~~6. Evapotranspiration deficit index (ETDI) at seasonal scale from 1991 to 1995. ~~Grey~~The grey color is painted over the grid cell where the ETDI is not statistically significant ~~in contrast~~compared to ~~counter-factual~~the counterfactual ensemble. The parameter AS on each panel ~~mark~~marks the percentage of land area ~~which~~that has shown statistically ~~significance~~significant dry or wet response after Mt. Pinatubo eruption.

3.5 Seasonal ~~**Plant Productivity Inferences**~~**plant productivity inferences**

SMDI (at depths of 0-2~~,~~ (0.6m), 2-4~~,~~ (0.6m-1.2m), and 4-6 feet~~)~~ (1.2m -1.6m)) and ETDI have proven helpful in analyzing the climatic impact of the Mt. Pinatubo eruption on a seasonal scale. Additionally, SMDI_2 (top 2 feet or 0.6 m) and ETDI have demonstrated ~~elements~~a slow development of drought conditions, beginning by the end of the year 1991 (SON season), reflecting a time lag between seasonal precipitation ~~on a seasonal scale~~patterns (Narasimhan and

Srinivasan 2005). Crucially, the seasonal depiction of drying/wet conditions via SMDI and ETDI provides a comprehensive overview of prolonged or recurrent dry/wet conditions in susceptible regions. Moreover, understanding these typical agricultural drought indices indicates potential effects on plant productivity at the seasonal scale.

~~Broadly the seasonal responses uncovered an interesting behavior in three more deeply explored regions.~~ In equatorial Africa, decreases in both SMDI and ETDI indicated that there was likely a negative impact on plant productivity. ~~On the contrary, the~~The Mediterranean region (encompassing the eastern Mediterranean and western Asian region) showed ~~increases in~~increased SMDI and ETDI, indicating a positive effect on plant productivity. Northern Asia, on the other hand, exhibited an increase in SMDI with a decrease in ETDI, ~~indicating~~suggesting that plant productivity likely decreased, but not because of water-based drivers.

3.6 High ~~Frequency Impact Pathway Evaluation~~frequency impact pathways evaluation

Here, we use the daily model output ~~on a daily scale~~ to calculate weekly drought indices in each grid cell. These weekly scale drought indices and changes in other atmospheric variables are explored at the regional scale to understand the associated land-atmosphere interactions ~~in terms of~~pertaining to higher-order impacts. ~~High~~The higher temporal resolution of these parameters is crucial for ~~analysis of~~analyzing different stages of the crop cycle in a region. Considering the complexity of the representation of spatial features, we selected three ~~different~~distinct regions (shown in Figure ~~8~~7 and detailed in ~~Table 2~~caption) in the northern hemisphere based on the climate response to Mt. Pinatubo in the seasonal analyses presented in Section 3.0. We followed the same strategy described in Section 2.3.1 to mask out the statistically insignificant grid cells using the counterfactual ensemble after creating the weekly time series for different drought indices and atmospheric parameters.

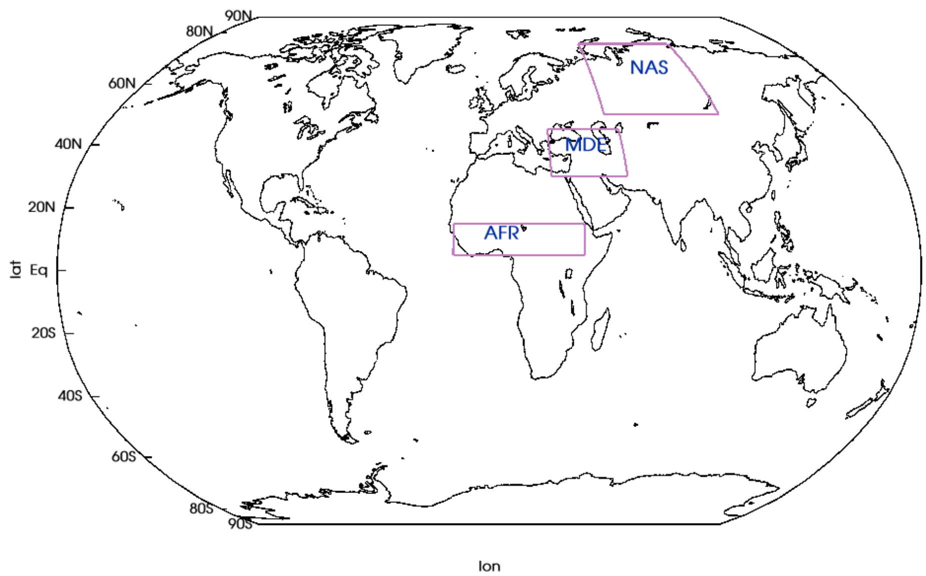


Figure ~~8~~7: Demarcation of the regions selected over tropics, Equatorial Africa Region (AFR; Lat: 5°N – 15°N, Lon: 15°W– 40°E), mid-latitude, Middle East Region (MDE~~)~~; Lat: 30°N – 45°N, Lon: 27°E – 60°E), and in the high latitudes, Northern Asia Region (NAS~~) as shown in table 2.~~; Lat: 50°N –75°N, Lon: 55°W –110°E).

~~Table 2. Table showing the details of regions demarcated to regional characteristics at a weekly scale.~~

~~Sr No.~~	~~Region Name~~	~~Region Stamp~~	~~Lat boundaries~~	~~Lon boundaries~~
~~1~~	~~Equatorial Africa Region~~	~~AFR~~	~~5° N – 15° N~~	~~15° W - 40° E~~
~~2~~	~~Middle East Region~~	~~MDE~~	~~30° N - 45° N~~	~~27° E - 60° E~~
~~3~~	~~Northern Asia Region~~	~~NAS~~	~~50° N - 75° N~~	~~55° E - 110° E~~

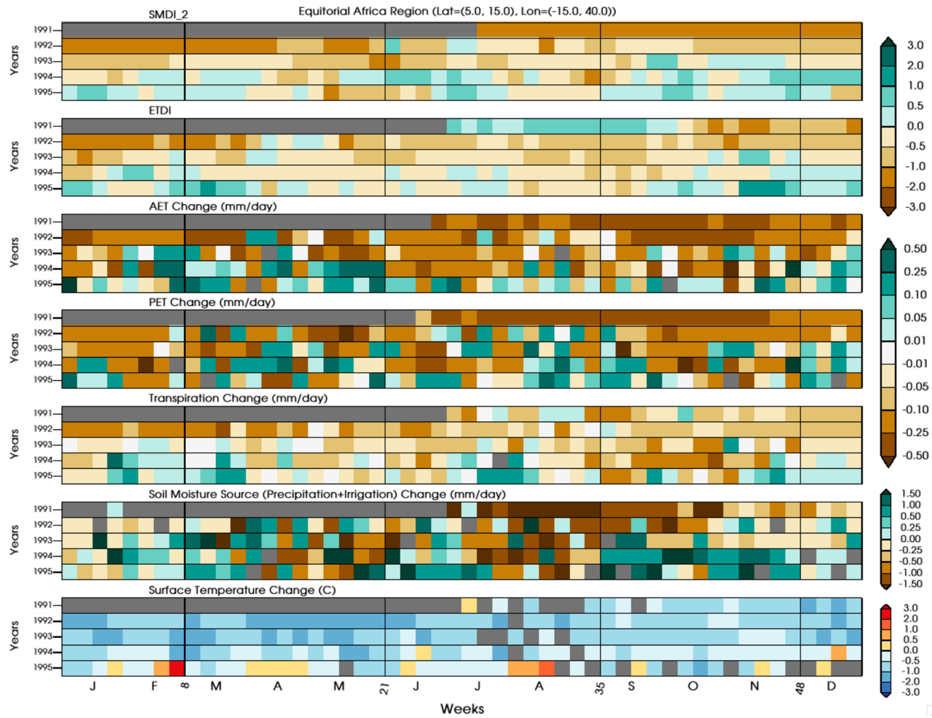


Figure 98. Spatially averaged drought indices (SMDI_2 & ETDI) and anomalies for other drivers (~~Surface Temperature, Precipitation plus irrigation,~~ Actual and Potential Evapotranspiration, ~~and~~ Transpiration, Moisture Source (Precipitation plus irrigation) and Surface Temperature) at weekly scale for the equatorial Africa region (Latitude = 5°-15° N, Longitude = 15° W- 40° E).

3.6.1 Equatorial Africa

Figure 98 shows the weekly response to volcanic forcing for the years 1991-1995 in terms of agricultural drought indices (SMDI_2 & ETDI), AET, PET, ~~AET,~~ transpiration, total soil moisture source, and surface temperature for an equatorial region in northern Africa. This region exhibits consistent statistical differences across the drivers on a weekly scale ~~and~~; thus ~~,~~ , for most of the ~~majority of~~ time ~~periods are~~period, this is unmasked, revealing the degree of ~~anomaly~~anomalous conditions.

This region lies between the latitude 5-15°° N, where the precipitation during the monsoon season shows a decrease in response to a southern migration of the inter-tropical convergence zone ~~in energetically deficit northern hemisphere due to volcanic aerosols preferentially reducing incoming radiation there~~ (Iles et al., 2013; Colose et al., 2016; Singh et al., 2023). Weekly precipitation change in the equatorial ~~African region~~Africa shows a significant deficit of more than 1.5 mm per day consistently for several weeks, especially during the JJAS monsoon season. This region also shows that a deficit in precipitation during the major precipitation season (JJAS) can result in a soil moisture deficit in the root zone in the following seasons (DJF and MAM in SMDI_2) and consequently affect the entire crop cycle. The root zone soil moisture, SMDI_2, also shows a persistent drying through 1993, and combined with the lack of precipitation, the potential for recharge is limited. Also, this region has no contribution from irrigation as a source of additional soil-~~-~~moisture, as shown in ~~figure S5~~Figure S7 (bottom panel) (Cook et al., 2020). Cumulative annual rainfall change over this region shows a deficit of 33.2, 9.5, and 3.2 mm per day for the ~~year~~years 1991, 1992, and 1993 and an increase of 10.5 and 13.6 mm per day for the ~~year~~years 1994 and 1995, respectively, where soil-moisture response shows a recovery from the dry conditions.

Hence, it is ~~no surprise~~unsurprising that ~~there is~~ a corresponding decrease in ETDI through 1993 ~~that~~ is consistent with this lack of moisture. However, the evaporative demand, as shown by surface temperature change, does not consistently decrease until September of 1991, and hence, ETDI is slow to show a ~~decrease~~response in the deficit index. After that point, evaporative demand decreases with lower temperatures ~~contributing to a decrease in ETDI.~~

~~However,~~, but the evapotranspiration is dominated by transpiration (Seneviratne et al 2010; Nilson and Assmann 2007 ~~and references therein~~), and so the majority of the decrease in ETDI is explained by the shown decrease in plant transpiration. ~~This~~As expected, this decrease in plant transpiration is~~, as expected,~~ well correlated with decreases in AET.

Conclusively, precipitation response in this region shows dominance in regulating the ecohydrological conditions. A substantial decrease in the weekly rainfall over the region perpetuates a root-zone water deficit ~~condition~~, resulting in decreased plant transpiration. Decreases in both SMDI_2 and ETDI thus indicate ~~the~~ developing agricultural drought conditions, which are confirmed by a decrease in the direct measure of plant transpiration.

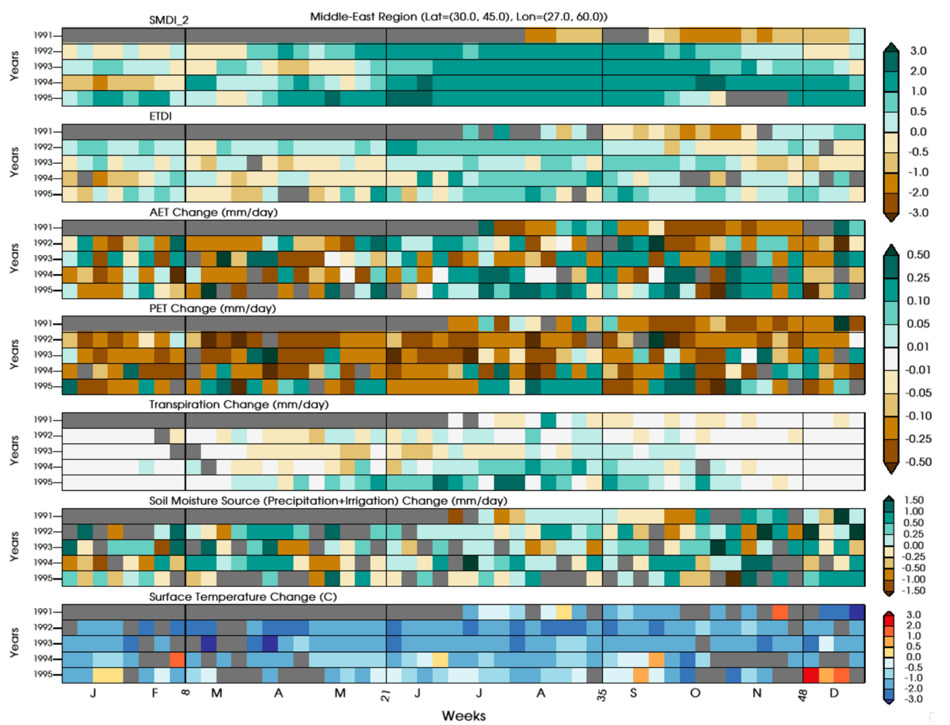


Figure ~~10~~9. Spatially averaged drought indices (SMDI_2 & ETDI) and anomalies for other drivers (~~Surface Temperature, Precipitation plus irrigation,~~ Actual and Potential Evapotranspiration, ~~and~~ Transpiration, Moisture Source (Precipitation plus irrigation) and Surface Temperature) at weekly scale for Middle East (MDE) Region (Latitude =30° N - 45° N, Longitude=27°-60° E; ~~eastern~~Eastern Mediterranean /~~ western~~Western Asian).

3.6.2 Middle East Region

Figure ~~10~~9 shows the region covering the eastern Mediterranean and the western Asian ~~region~~regions where rainfall ~~shows a slight increase~~slightly increased after the Mt. Pinatubo eruption. Additionally, this region exhibits a significantly positive trend in ~~the~~ irrigation practices post-~~1050~~1950, with a substantial peak over the eastern Mediterranean region following the Mt. Pinatubo eruption (Cook et al., 2020; Figure 1 and 2).

In the eastern Mediterranean, wet and cold autumns and winters persist for several years after the Mt. Pinatubo eruption, offering significant root zone recharge potential. The summer months, in general, reflect a slightly uncertain model response in the regional rainfall, with some weeks of deficit and some ~~of~~ excess, but an additional water supply ~~of water~~ through ~~the~~ irrigation contributes to the overall moisture content in the region (Figure ~~S5~~S7). Root zone soil moisture~~,~~ (SMDI_2~~, shows ample~~) indicates sufficient water ~~during~~availability throughout the growing seasons ~~through~~during the entire analysis period. ~~Taken together, it is clear~~Overall, the findings demonstrate that this region is not moisture-limited ~~and there is sufficient~~ , with adequate precipitation and irrigation ~~supply to recharge~~ ensuring the replenishment of root zone moisture as plants grow. Cumulative weekly anomalies show that precipitation change in 1991 is slightly negative (-0.5 mm per day~~)~~), but an increase in annual rainfall of 13.8, 8.0, 10.9, and 4.5 mm per day is simulated for the ~~year~~years 1992, 1993, 1994, and 1995, respectively. ~~Implemented irrigation over~~Irrigation implemented across this ~~middle east~~Middle East region ~~shows~~exhibits a strong positive trend ~~for the period~~from 1950~~-~~ to 2005 (Cook et al., 2020~~), and~~).

Notably, a ~~substantial~~significant cumulative increase in irrigation of 0.5, 1.3, 1.3, 0.8, and 0.9 mm per day ~~in the irrigation for~~ during the years 1991 to 1995 ~~serves as the~~ provides an additional source of moisture supply ~~over~~for the region (Cook et al., 2020). ~~Thus,~~This irrigation ~~supplies water especially in~~is particularly crucial during the summer months ~~when~~ , compensating for rainfall ~~change shows a few~~deficits lasting several weeks ~~of deficit~~ and ~~contributes~~contributing 10~~-~~–20% of ~~the~~ soil~~-~~ moisture source ~~change~~changes (Figure ~~S5~~S7).

The corresponding increases in ETDI and AET ~~reflect~~indicate the ~~ample source of~~ abundant water ~~available~~availability for transpiration in the region. ~~Transpiration is again~~While transpiration remains temporally correlated with AET, ~~but~~ the increases are less ~~well~~ pronounced. ~~At the same time~~Simultaneously, there is a ~~decrease~~decline in PET response ~~correlated~~, which is associated with ~~the stronger~~ a more significant temperature decrease in ~~temperature in~~ this region ~~as~~ compared to equatorial Africa. The ~~decrease~~reduction in PET ~~coupled~~, combined with the increase~~/~~ or maintenance ~~in~~of AET ~~(~~through transpiration~~) combine~~, leads to ~~result~~an increase in ~~increased~~ ETDI. ~~Thus, in general~~Consequently, agricultural productivity ~~is positively affected~~ in this region ~~as there is~~ is generally positively impacted, as ample moisture ~~to~~ provides essential support ~~it. However, there are still heterogenous~~. Nevertheless, the data reveals heterogeneous patterns ~~in this data showing~~, indicating that 1993~~, for instance,~~ may have ~~had some impact on~~influenced plant productivity with a positive but lower~~-~~ magnitude ETDI, inconsistent AET, and ~~decreased~~reduced transpiration.

Regardless of the presence of a volcanically induced response ~~or not~~, the weekly scale analysis demonstrates its importance by virtue of an example from ~~the year~~ 1993, where rainfall deficit is produced during the 15th~~,~~ and 16th weeks (April) of the year. Combined with ~~low~~lower SMDI_2, this ~~could result in a lack of~~may lead to insufficient moisture availability during a

~~crucial~~critical stage of the crop cycle. ~~Given the~~The duration~~, this~~ of such moisture deficits could significantly ~~influence the~~ impact overall seasonal crop production. ~~Thus~~Consequently, even if ~~the majority of the crop cycle possess~~ favorable conditions~~, negative impacts at~~ prevail for most of the crop cycle, adverse effects during essential phases ~~of the crop cycle~~ can ~~crucially affect production~~critically influence yields in ways that seasonal averages ~~would be unable~~fail to ~~reveal~~capture.

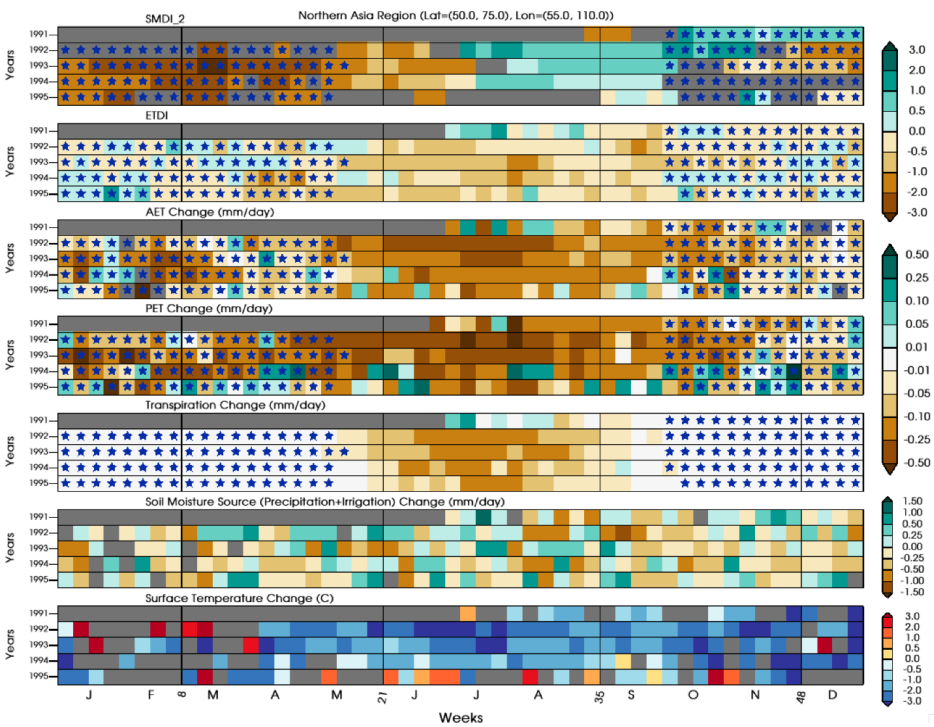


Figure ~~11~~10. Spatially averaged drought indices (SMDI_2 & ETDI) and anomalies for other drivers (~~Surface Temperature, Precipitation plus irrigation,~~ Actual and Potential Evapotranspiration, ~~and~~ Transpiration, Moisture Source (Precipitation plus irrigation) at weekly scale Northern Asia Region (Latitude =50° N - 75° N, Longitude=55°- 110° E). Blue stars represent the weeks with average surface temperature below freezing point.

3.6.3 Northern Asia

Finally, we selected a region (NAS) in higher latitudes to explore the interplay between the various drivers governing the conditions for plant productivity. ~~Again, this~~This region consistently exhibits ~~consistent statistical~~statistically significant differences across ~~the~~ drivers on a weekly scale. However, ~~with~~ higher latitudes ~~also comes~~experience strong seasonal controls ~~over~~on plant productivity, with below-freezing temperatures~~, shown with~~ (indicated by blue stars,) halting ~~productivity. Hence~~growth. Therefore, our analysis ~~here will focus~~focuses on months ~~during which plants can grow~~when plant growth is possible (~MJJAS).

Precipitation changes ~~are highly uncertain~~ over the entire analysis period~~, but in general~~ are highly uncertain. However, there is generally a slight trend ~~towards~~toward increased precipitation from ~~Nov~~November 1991~~-~~ to June 1992, followed by ~~decreased precipitation~~a decline through 1994. As shown in ~~Fig~~Figure S5, the ~~irrigation~~ contribution of irrigation to soil moisture in this region is negligible. Cumulative weekly precipitation anomalies ~~show~~indicate an annual increase of 0.05 mm per day ~~for year~~in 1991~~ and decrease~~, followed by decreases of -2.0, -4.1, -6.8, and -1.0 mm per day ~~for the years~~from 1992 to 1995, respectively. Alternatively, root zone moisture shows ~~ample~~that sufficient water available to plants during the JAS (July-August-September) growing months after a ~~strong~~substantial deficit in the early MJ (May-June) months. Certainly, ~~in these~~during the summer months, the melting of frozen surfaces and snow supplies moisture ~~in~~into the upper layers~~ to become~~, resulting in wet ~~accounting~~conditions, which accounts for this strong dichotomy.

However, there ~~are not~~were no corresponding increases in ETDI and AET ~~after~~following the 1991 season. This indicates that ~~even though there is~~despite ample water, plants are still not growing; this is conclusively confirmed by the decrease in transpiration starting in 1992.

Meanwhile, the simultaneous ~~decrease in~~reduction of PET response is correlated with the ~~strongest decrease~~most substantial decline in temperature, on the order of 2-3~~°~~° C, for ~~the three regions.~~this region.

Unlike the other two regions for which SMDI_2 and ETDI exhibited similar wet/dry patterns, this ~~location~~region shows diverging patterns. ~~Broadly~~Overall, this ~~reveals~~indicates that ~~even though there is~~although moisture is available to support plant productivity, ~~the moisture~~it is not being effectively utilized. ~~Hence~~Therefore, other factors must be responsible for the ~~cause of decreased~~decrease in plant transpiration and ETDI. The ~~stronger decrease of~~ more significant decline in PET compared to AET ~~indicates~~suggests that temperature ~~may be~~is playing a role ~~here. Temperature~~ . Since temperature is ~~a direct proxy of decreased~~directly related to reduced incident radiation~~. Hence,~~, the combined effects of temperature and radiation ~~effects~~ are likely the ~~most important controls on decreased~~primary factors controlling the reduced plant productivity in this region, ~~not~~rather than moisture conditions.

4.0 Conclusions

~~This study has used the Earth system modelling framework to explore the mechanisms by which the 1991 Mt. Pinatubo eruption affected the hydroclimatic conditions and water-based drivers of plant productivity. NASA GISS ModelE2.1 with the interactive chemistry and aerosol microphysical module (MATRIX) has demonstrated a successful simulation of microphysical properties (effective radius of order ~0.5 µm, aerosol extinction of ~0.21) of volcanic aerosol with induced radiative effect of longwave, shortwave, and net forcing of order of +3 Wm^{-2}, 8 Wm^{-2} and -5 Wm^{-2} respectively. This is consistent with the observations and other estimates (Russell et al., 1996; Bingen et al., 2004; Stenchikov et al., 1998; Bauman et al., 2003, Lacis et~~

al., 1992, Lacis 2015; Stenchikov et al., 1998; Hansen et al., 1992; Minnis et al., 1993; Brown et al 2024). The temperature response pathway shows Mt. Pinatubo eruption affected global surface cooling by ~0.5 °C with corresponding tropical lower stratosphere warming of 2-3 °C for several years after the eruption. This is consistent with the observations and other modeling estimates (Hansen et al., 1996; Parker et al., 1996; Stenchikov et al., 1998; Minnis et al., 1993; Kirchner et al., 1999; Ramachandran et al., 2000; Dutton and Christy 1992; Brown et al 2024). The GISS model simulates regional patches of decreases in rainfall of the order of 1 mm per day over the tropics and northern hemisphere regions (consistent with Joseph and Zheng, 2011; Liu et al., 2016; Trenberth and Dai, 2007), but the overall response of rainfall is highly uncertain. This study has endeavored to explore the secondary impacts of a volcanic eruption beyond the changes in radiation and temperature by examining agricultural drought indices to better infer impacts to plant productivity. Droughts are among the prime factors affecting regional crop yield at any stage of the crop cycle (Ben Abdelmalek and Nouiri, 2020; Leng and Hall, 2019; Raman et al., 2012). Both SMDI and ETDI represent the developing short- and longer-term conditions which support plant productivity, especially for agricultural applications. SMDI represents excess/deficit of soil moisture in different layers, whereas ETDI represents the active interaction between the land and atmosphere under perturbed climate conditions. An increase in the gap between the potential evapotranspiration (PET) and actual evapotranspiration (AET) represents the increased water stress condition either by increased potential evapotranspiration (water demand) or by the decrease in water available for evapotranspiration (lower AET). These drought indices confirm the moisture source based dry and wet pattern in early 1992 and the following years over the tropical and northern hemispheres mid-latitude regions correspondingly as a response to the volcanic forcings due to the Mt. Pinatubo eruption. Using both drought indices, we conclude that approximately 10-15% of land region shows statistically significant dry or wet patterns in the volcanically perturbed climate conditions for 1992 and 1993. The fraction of land region showing a significant dry or wet response range between 5-10% for the next two (1994 and 1995) years. Broadly, the seasonal responses uncovered interesting behavior in three regions which we explore more deeply. In equatorial Africa, decreases in both SMDI and ETDI indicated that there was likely a negative impact on plant productivity while in a contrary manner the Middle East region showed increases in SMDI and ETDI indicating a positive impact on plant productivity. Northern Asia in comparison exhibited an increase in SMDI with a decrease in ETDI indicating that plant productivity likely decreased, but not because of water-based drivers.

UsingThis study utilized the NASA GISS ModelE2.1 (MATRIX) Earth system modeling framework to investigate the mechanisms by which the 1991 Mt. Pinatubo eruption influenced hydroclimatic conditions and water-based drivers of plant productivity. The simulation successfully reproduced key microphysical properties ($R_{eff} \approx 0.5$ µm, AOD ≈ 0.22), radiative forcing (~-5 Wm^{-2}), surface cooling (~0.5°C), and regional rainfall changes consistent with previous studies. The study further examined secondary impacts of the eruption, beyond changes in radiation and temperature, by analyzing agricultural drought indices to better assess its effects on plant productivity. Two metrics, SMDI and ETDI, which account for land-atmosphere interactions, were utilized to capture the progression of short- and long-term conditions affecting plant productivity, particularly in agricultural contexts. These drought indices confirm the moisture-driven dry and wet patterns observed in early 1992 and the following years over the tropical regions and mid-latitudes of the Northern Hemisphere, respectively, as a response to the radiative perturbation caused by the Mt. Pinatubo eruption. Based on both drought indices, we conclude that approximately 10-15% of land areas exhibit statistically significant dry or wet patterns under the volcanically altered climate conditions of 1992 and 1993. The fraction of land region showing a significant dry or wet response range between 5-10% for the next two (1994 and 1995) years. In equatorial Africa, seasonal decreases in both SMDI and ETDI suggested a likely negative impact on plant productivity. In contrast, the Middle East showed increases in both SMDI and ETDI, indicating a positive effect on plant productivity. Northern Asia, by comparison, exhibited an increase in SMDI alongside a decrease in ETDI, implying a reduction in plant productivity, though not driven by water-related factors.

Motivated by these key pattern differences ~~as motivation~~, we ~~deepened~~extended our analysis of ~~these~~the drought indices ~~using~~by incorporating higher temporal (weekly) frequencies ~~and by incorporating~~ along with AET, PET, and transpiration ~~directly. In general, these~~. These regional analyses ~~possess~~generally exhibit much stronger statistical significance on ~~the~~a weekly scale~~,~~ and ~~they~~ further ~~confirmed~~confirm the ~~seasonally~~ season-based inferences described above. Further, weekly drought indices show the temporal variability characteristics in the signal, which also demonstrates the utility of explaining the effectiveness of short-term dry/wet conditions corresponding to a regional crop cycle. In locations ~~where there is~~with insufficient/excess soil moisture, there is a corresponding decrease/increase in evapotranspiration (AFR/MDE) and hence decreased/increased plant productivity.

Kandlbauer et al., (2013) examined crop responses (using C3 and C4 grasses as proxies) to the 1815 Tambora eruption using the HadGEM-ES model in three regions very similar to those in our study. Their findings suggest that plant productivity decreases with positive changes in soil moisture in the higher-latitude Asian region. In the mid-latitudes over the Southern Europe/Middle East region (adjacent to our MDE region), volcanic eruptions may enhance plant productivity by providing additional soil moisture through increased rainfall. However, in the MDE region in our study, we found that the applied irrigation also benefits soil moisture supply along with the increased rainfall. Furthermore, both studies report a decrease in productivity in the tropical region. In general, these results complement the findings of this study, which suggest that if sufficient water is available in the Southern Europe/Middle East region, volcanic eruptions may enhance plant productivity. In contrast, in the far northern latitudes, water is not the primary driver of plant responses, and productivity is likely to decline. Seasonal-scale changes in gross primary productivity (GPP) confirm the regional trends in plant productivity following the eruption. The simulations show a more pronounced decrease in GPP in the northern high-latitude region and a significant increase in GPP over the European and Mediterranean regions. Additionally, distinct patterns of decrease and increase in GPP are simulated in the tropical northern and southern regions, respectively (Figure S9).

This ~~work~~study is the first to conclusively ~~show~~demonstrate that there is an excess of root-zone soil moisture in high~~ latitudes ~~-latitude regions (NAS) ~~which is not being utilized by~~that plants ~~to grow establishing the main control is likely ~~are not utilizing for growth, indicating that temperature and radiation ~~based~~are likely the primary controlling factors, thus confirming ~~the results of~~previous findings (Krakauer and Randerson, 2003) and (Dong and Dai, 2017). The intricate nature of the compounded response, particularly ~~regarding the ~~in relation to soil moisture-~~based~~driven impact pathways in tropical regions and ~~higher latitudes across~~high-latitude areas of the Northern Hemisphere, highlights the ~~northern hemisphere, also underscores the necessity of broadening the scope of~~need to expand the investigation beyond soil moisture and land-atmosphere interactions. The current ~~setup~~configuration of the NASA GISS model ~~effectively runs using~~operates with prescribed vegetation with static plant functional types and leaf area index~~, and the inclusion of~~. Incorporating dynamic vegetation could be ~~crucial~~essential for ~~adding~~capturing interactive land surface responses. ~~Also, assessing~~Additionally, evaluating the influence of ~~the~~ regional and local ~~biome~~biomes on photosynthesis ~~rate~~rates could ~~provide a more detailed understanding of~~offer deeper insights into how these processes ~~specifically~~ respond to the ~~climate impact~~climatic impacts of volcanic forcings. McDermid et al. (2022) have demonstrated the sensitivity of regional hydroclimate to the local changes in soil organic carbon changes using the soil moisture content. The results presented in this study ~~in terms of~~regarding soil-moisture-based drivers to ~~the~~ plant productivity and surface temperature response in the northern ~~hemisphere~~hemisphere's high latitudes also ~~hint~~hinted towards the dominance of temperature effects on enhanced carbon sink in terms of soil and plant respiration and reduced NPP (Krakauer and Randerson, 2003; Lucht et al., 2002). Meanwhile, water-based drivers ~~dominate~~predominantly influence productivity responses in ~~multiple~~many tropical and ~~sub-tropical~~subtropical regions. Our ~~results illustrate~~findings demonstrate that soil~~-~~ moisture~~-based~~ conditions ~~in the~~across different regions can ~~be useful for evaluating and understanding~~provide valuable insights into the full impacts on ~~the~~ agricultural ~~yield~~yields and regional carbon sink ~~response if the~~ responses, particularly under scenarios involving changes in dynamic vegetation and crop cover ~~changes~~. A recently developed fully demographic dynamic vegetation model (ModelE-BiomE v.1.0 (Weng et al., 2022)) ~~with~~incorporates interactive biophysical and biogeochemical ~~feedback~~feedbacks between climate and land systems ~~for~~within the NASA GISS ModelE framework. This model could be ~~helpful~~instrumental in evaluating ~~the~~ carbon cycle ~~response~~responses under such forcings.

Code/Data availability.

Details to support the results in the manuscript is available as supplementary information is provided with the manuscript. GISS Model code snapshots are available at https://simplex.giss.nasa.gov/snapshots/ (National Aeronautics and Space Administration, 2024) and calculated diagnostics are available at zenodo repository (https://zenodo.org/records/12734905) (Singh et al., 2024). However, raw model output and data at high temporal (daily) resolution and codes are available on request from author due to large data volume.

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Author's contributions

RS, KT, DB, LS and KM identified the study period in consultation with the other authors and RS, KT, DB, LS and BW designed the underlying simulations strategies. RS and KT implemented it and performed the simulations using NASA GISS ModelE. RS and KT have performed the analysis. RS created the figures in close collaboration with all authors. RS wrote the first draft of the manuscript, and all other authors has contributed the writing of subsequent drafts. All authors contributed to the interpretation of results.

Competing interests

One of the co-authors is member of the editorial board of Atmospheric Chemistry and Physics.

Short Summary

Analysis of post-eruption climate conditions using the impact metrics is crucial for understanding the hydroclimatic responses. We used NASA's Earth system model to perform the experiments and utilize the moisture-based impact metrics and hydrological variables to investigate the effect of

volcanically induced conditions that govern plant productivity. This study ~~demonstrates~~highlights the ~~Mt. Pinatubo's~~ impact of the Mt. Pinatubo eruption on the drivers of plant productivity~~ and~~, as well as the regional and seasonal dependence of ~~different~~these drivers.

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