

## Article

# Multidecadal Variation Characteristics and Mechanism Analysis of Indian Summer Monsoon Precipitation During the Little Ice Age

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## Abstract

The Indian monsoon is an important component of the tropical climate system. Studies suggest that both precipitation from the NNU-2K AF experiments and Little Ice Age (LIA) proxy data reveal a significant 56-year period in the Indian summer monsoon (ISM). Volcanic activity influences the multi-year and decadal characteristics of Indian monsoon precipitation. A comparative analysis of multi-decadal variations in ISM precipitation from the AF experiments and the single-factor sensitivity experiments shows a correlation of 0.45 ( $p < 0.05$ ), indicating dependence on volcanic activity. The 56-year period of ISM precipitation in the AF experiments is consistent with both the single-factor sensitivity experiments and precipitation influenced by volcanic activity. Further analysis reveals that cooling over Eurasia and warming of the Indian Ocean weaken the thermal contrast between land and sea, thereby reducing ISM intensity and decreasing ISM precipitation. Conversely, enhanced volcanic activity induces widespread cooling across the Northern Hemisphere, which shifts the Intertropical Convergence Zone (ITCZ) southward. This reduction in evaporative capacity and moisture content within the monsoon region ultimately decreases precipitation across the monsoon belt.

**Keywords:** Indian summer monsoon precipitation; volcanic activity; multidecadal variation; climate simulation

## 1. Introduction

The Indian summer monsoon (ISM) is one of the most significant monsoon systems in the Earth's climate system [1,2]. Its precipitation patterns are among the most prominent features of the global climate system [3]. Known as the South Asian Summer Monsoon or the Southwest Monsoon, it is considered a crucial component of the global climate system. Approximately 80% of precipitation in South Asia is controlled by the ISM, while precipitation in the western Indochina Peninsula and southwestern China is also notably impacted. The influence of global warming on precipitation has been extensively examined in climatological research [4–6], and historical warm periods have similarly received considerable scholarly attention [7,8]. The investigation of precipitation during historical warm periods facilitates the understanding of the characteristics and causes of modern warm periods, whereas cold periods have been comparatively understudied. Although rising temperatures dominate global warming trends, intermittent cold spells occasionally occur. Understanding precipitation patterns during historical cold periods is essential for improving predictions of future cold events and their underlying mechanisms.



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The study of the LIA has long been an important topic in climate science. The concept of the LIA was first proposed by Matthes in 1939 [9] and, in recent decades, has been used specifically to refer to the cold period following the Medieval Climate Anomaly during the past millennium. After more than half a century of debate, the concept is now widely accepted by geographers, geologists, and climatologists [10,11]. Paleoclimate reconstructions indicate that volcanic activity during the LIA was intense, with numerous major eruptions [12–14]. Volcanic eruptions are widely regarded as one of the principal drivers of the LIA [15,16], and volcanic activity played a significant role in climatic changes during its multidecadal duration [17–20]. Such eruptions provide valuable opportunities to observe the climate system's response to external forcing [21,22].

Changes in the Indian monsoon during the LIA are believed to be driven by the interaction of multiple climate systems. Research indicates that reduced solar radiation is considered a key factor in triggering and regulating the intensity of the ISM precipitation, with a significant correlation observed between diminished solar radiation and weakened monsoons during the LIA [23]. Additionally, variations in sea surface temperatures across the Indo-Pacific Ocean exert a substantial influence on monsoon circulation. Studies have highlighted a certain degree of association between ENSO (Southern Oscillation) and the ISM [24]. ENSO also influenced ISM precipitation during the LIA. When ENSO weakened, ISM precipitation decreased [25]. Other studies indicate that sea surface temperatures and large-scale circulation patterns also affected the ISM precipitation during the LIA [26]. The weakening of the North Atlantic Meridional Overturning Circulation (AMOC) and associated Northern Hemisphere cooling events were also key factors influencing ISM precipitation during the Little Ice Age [27]. ISM precipitation is profoundly influenced by the position and intensity of the Intertropical Convergence Zone (ITCZ), whose displacement is also considered a potential driving mechanism. When the ITCZ is weaker and shifted southward, ISM precipitation decreases [28,29]. Some scholars further propose that volcanic forcing drives multidecadal monsoon variability at hemispheric and global scales by affecting sea surface temperatures, ENSO, and the Atlantic Multidecadal Oscillation (AMO) [27]. On a global scale, large-scale volcanic eruptions may trigger a reorganization of the Hadley circulation, shifting the ITCZ away from hemispheres with higher aerosol concentrations. Studies combining tree-ring data with volcanic activity records suggest that major tropical volcanic eruptions cause short-term global cooling, which in turn affects precipitation in monsoon regions [30,31]. The studies mentioned above provide insights into the factors influencing ISM precipitation during the LIA. However, previous research has focused solely on either hemispheric or global scales or on the combined effects of atmospheric-oceanic-solar radiation forcing on ISM precipitation during the LIA. These studies did not conduct sensitivity experiments targeting individual volcanic forcing to isolate the contributions of these external forcings to ISM precipitation during the LIA. The mechanisms by which volcanic activity altered ISM precipitation during the LIA remain unclear. This study employs a series of experiments using the Community Earth System Model (CESM) to elucidate how volcanic activity influences the characteristics of Indian monsoon precipitation. The simulated results are compared with a dataset of multi-use indicators. We aim to reveal the spatiotemporal evolution of ISM precipitation during the LIA and gain deeper insights into the key role of external forcings in its variability. We investigate the response mechanisms of volcanic forcing to the periodicity and intensity of ISM precipitation during the LIA and elucidate its underlying mechanisms.

## 2. Materials and Methods

The dataset utilized in this study is a global climate dataset spanning the past 2000 years, which is derived from the numerical integration of the Community Earth

Sys-tem Model (CESM) developed by the National Center for Atmospheric Research in the United States and designated as NNU-2K [32]. The initial external forcing of the model is based on the condition of 1850 AD, and 2400 years are calculated on this basis. The following 2000 model years are taken as the control experiment results for the past 2000 years. For other experiments, the last year of the Ctrl experiment is used as the initial field for integration calculations. A series of climate simulations over the past 2000 years was conducted, including the all-forcing experiment (AF), control experiment (Ctrl), total solar irradiation experiment (TSI), land cover and land use experiment (LUCC). The vertical resolution consisted of 26 layers, with a horizontal resolution of  $3.75^\circ \times 3.75^\circ$ . The time resolution is monthly. Proxy data include Jhumar  $\delta^{18}\text{O}$  from JHU-1Cave [33], Kelong tree-ring  $\delta^{18}\text{O}$  from the Northwest Himalaya [34], and Shi  $\delta^{18}\text{O}$  from South Asia tree-ring  $\delta^{18}\text{O}$ , which is a composite of 15 tree-ring data [35]. The JHU-1Cave stalagmite record spans 604 years. The Keylong and South Asia datasets are tree-ring records with temporal spans of 860 and 1104 years, respectively, both possessing annual temporal resolution. According to the global monsoon definition proposed by Wang and Ding [36], monsoon regions are classified as those where total ISM exceeds winter precipitation by at least 300 mm, and ISM constitutes more than 55% of the annual total. According to the definition, the red area is the Indian monsoon region,  $8^\circ\text{--}30^\circ\text{ N}$  and  $68^\circ\text{--}105^\circ\text{ E}$  (Figure 1). The ISM season is typically defined as June, July, August, and September (JJAS).

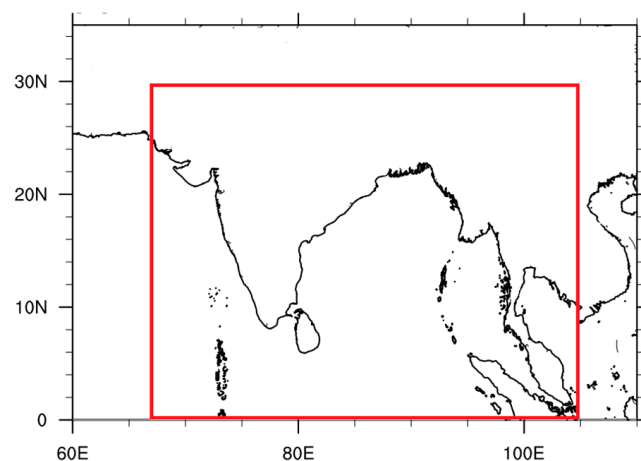


**Figure 1.** The Indian summer monsoon region (within the red box).

### 3. Results

#### 3.1. Multidecadal Variation Characteristics of ISM Precipitation During the LIA

The LIA refers to a century-scale period from the 15th to the 19th centuries, characterized by cooler temperatures and glacial expansion, constituting a cold phase of climate variability. Numerous studies indicate that this epoch was primarily initiated by volcanic eruptions [10,11], offering valuable insights into the analysis of potential future cold periods induced by volcanic activity. To identify multidecadal variations in precipitation patterns of the ISM throughout the LIA, an 11-year moving average was applied to both temperature and precipitation time series. Figure 2 illustrates the temperature and precipitation changes in the ISM region during this period (Figure 2a). Regional temperatures exhibited pronounced multidecadal trends, while precipitation displayed comparable periodic behavior. As shown in Figure 2b, ISM precipitation exhibited a distinct 56-year period during the LIA (Figure 2b).

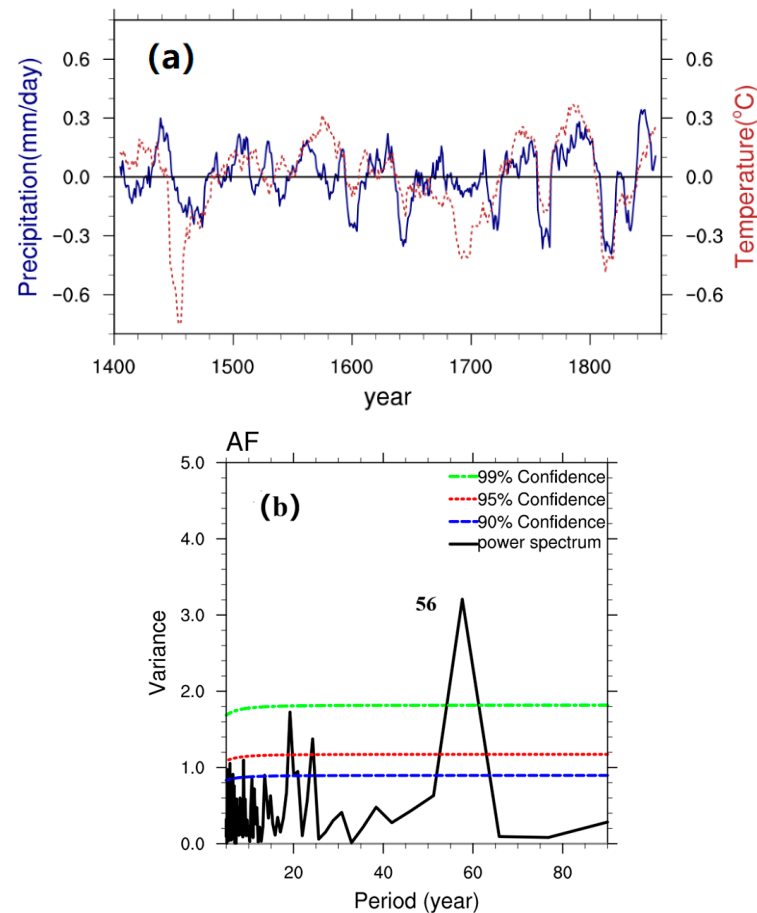


**Figure 2.** (a) Time series of summer average surface temperature (°C, red line) and precipitation (mm/day, blue line) of the ISM precipitation during the LIA (1400–1860) relative to the past 2000 years, based on the AF experiment (temperature and precipitation data were smoothed using an 11-year moving average). (b) Periodic analysis of summer monsoon precipitation in India during the LIA. The blue line indicates significance at the 90% confidence level, the red dashed line indicates the 95% confidence level, the green dashed line indicates the 99% confidence level, and the black solid line represents the periodic variation in precipitation.

Figure 3 depicts the power spectral period analysis of simulated and reconstructed ISM precipitation during the LIA. The AF experiment precipitation data reveal a period of approximately 56 years, passing the 95% significance level test. To validate reliability, the periodic variations in ISM precipitation were further analyzed using LIA data. The figure below shows the power spectrum period analysis of ISM precipitation simulated by the CESM model NNU-2K and reconstructed ISM precipitation. These are the AF experiment precipitation (AF) series, proxy data from Jhumar (stalagmite data), proxy data from Kelong (tree-ring data), and proxy data from Shi (tree-ring data). As shown in Figure 3a, the AF ISM experiment precipitation demonstrates a 56-year period that passes the 95% significance level test. The Jhumar, Kelong, and Shi proxies also exhibit similar 56-year periods, all passing the 95% significance level test (Figure 3b–d). These results confirm that the CESM model simulation data, NNU-2K, can accurately simulate the ISM precipitation over a 56-year period during the LIA.

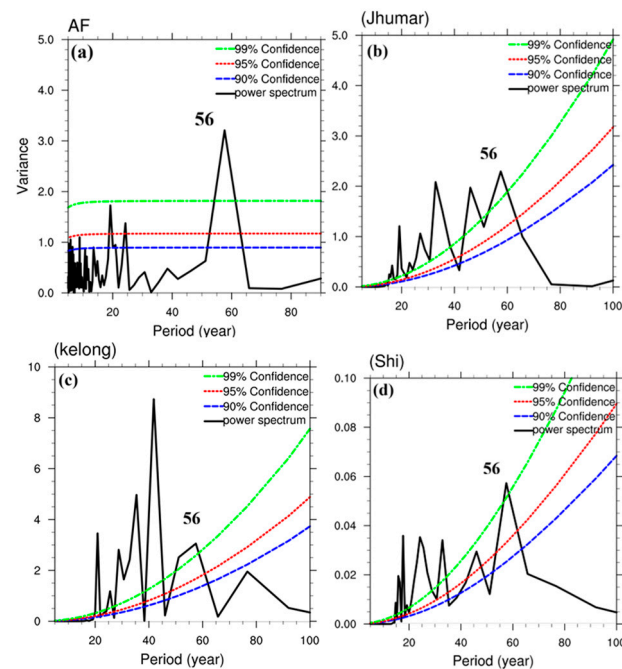


**Figure 3.** Power spectrum analysis of AF precipitation data and proxy data from the ISM region during the LIA (1400–1860). (a) AF represents simulated AF ISM experiment precipitation, (b) proxy data Jhumar  $\delta^{18}\text{O}$  from JHU-1Cave [33], (c) Kelong tree-ring  $\delta^{18}\text{O}$  from the Northwest Himalaya [34], and (d) Shi  $\delta^{18}\text{O}$  from South Asia tree-ring  $\delta^{18}\text{O}$ , which is a composite of 15 tree-ring datasets [35]. The blue line indicates a 90% confidence level test, the red dashed line indicates a 95% confidence level test, the green dashed line indicates a 99% confidence level test, and the black solid line indicates the periodic variation in precipitation.

The multidecadal variation in precipitation in the ISM region during the LIA is characterized by a distinct dipole pattern, typically showing a “positive–negative” spatial distribution from the southwestern to northeastern regions. Additionally, two principal centers are identified: one located in the western Indian Peninsula ( $16^{\circ}$ – $22^{\circ}$  N,  $72^{\circ}$ – $80^{\circ}$  E) and another in the southern Bay of Bengal marine area ( $14^{\circ}$ – $22^{\circ}$  N,  $86^{\circ}$ – $100^{\circ}$  E) (Figure 4).

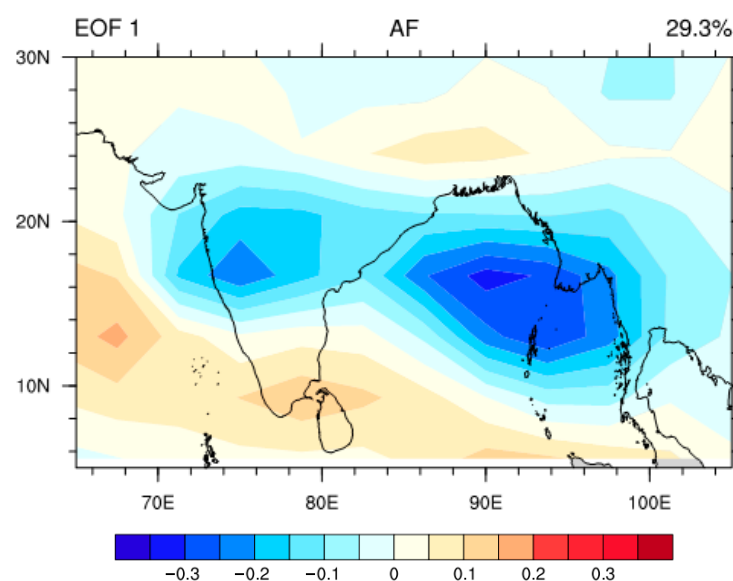


**Figure 4.** The EOF pattern of Indian summer monsoon precipitation (JJAS) during 1400–1860, derived from the NNU-2K after an 11-year sliding average.

### 3.1.1. Attribution of Time Characteristics of Multidecadal Variation in ISM Precipitation During the LIA

Several studies have suggested that intense and frequent volcanic activity is a characteristic period of temperature and precipitation anomalies that led to the LIA [37]. The Little Ice Age was a period marked by frequent volcanic activity, with each eruption typically releasing vast quantities of volcanic ash and other materials into the atmosphere. The climatic effects of volcanic activity exhibit a certain degree of lag, influencing global climate patterns for the subsequent 2–3 years [38,39]. The cumulative impact of numerous volcanic events may trigger multidecadal variations in Indian monsoon precipitation—a key issue explored in this paper. To investigate how volcanic activity triggers multidecadal-scale variations in precipitation, we analyzed the mechanism by which volcanic activity triggers decadal variations in ISM precipitation during the LIA. The three reconstructed ISM precipitation have strong periodic signals from 1400 to 1860, with a peak lasting 56 years (Figure 3). Therefore, the simulated data also focused on the same period. To confirm the role of volcanoes, we selected two identical time periods based on the magnitude and frequency of volcanic eruptions and defined 740–1200 as weak volcanic periods and 1400–1860 as strong volcanic years. The LIA is a strong volcanic period based on volcanic eruption magnitude and intensity (Figure 5). The subsequent analyses focus on these two distinct historical phases.

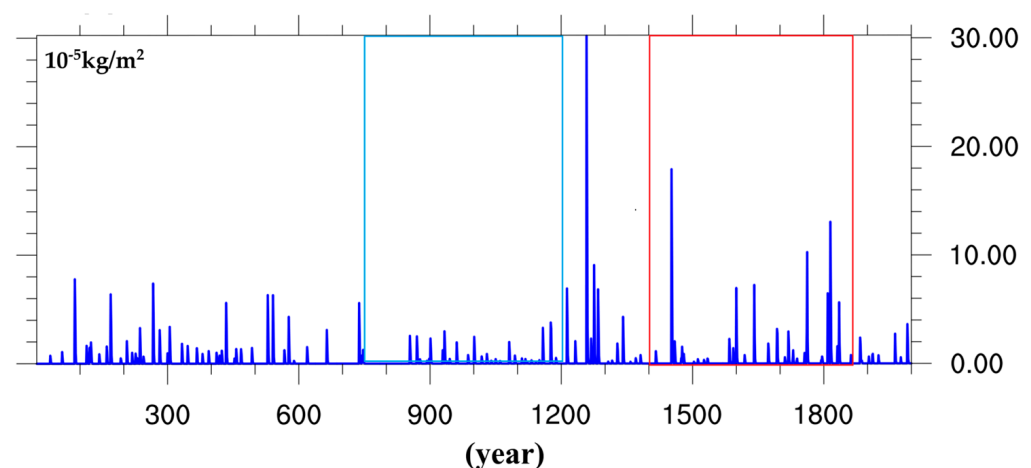


**Figure 5.** External forcing sequence of volcanic activity over the past 2000 years, classified according to differences in volcanic eruption intensity. The blue box indicates weak volcanic years from 740 to 1200, and the red box indicates strong volcanic years from 1400 to 1860, with units of  $10^{-5} \text{ kg/m}^2$ .

Figure 6 shows the correlation analysis between AF experiment precipitation and volcanic single-factor experiments precipitation during the strong years (1400–1860). The correlation coefficients for AF with TSI, Vol, GHGS, and LUCC experiments were 0.20 (32), 0.45 (31), 0.1 (36), and 0.007 (36), respectively. Notably, the correlation coefficient of 0.45, observed between AF and Vol experiments precipitation, passed the 95% significance test, indicating that ISM precipitation was predominantly influenced by volcanic activity on a multidecadal scale (Table 1).

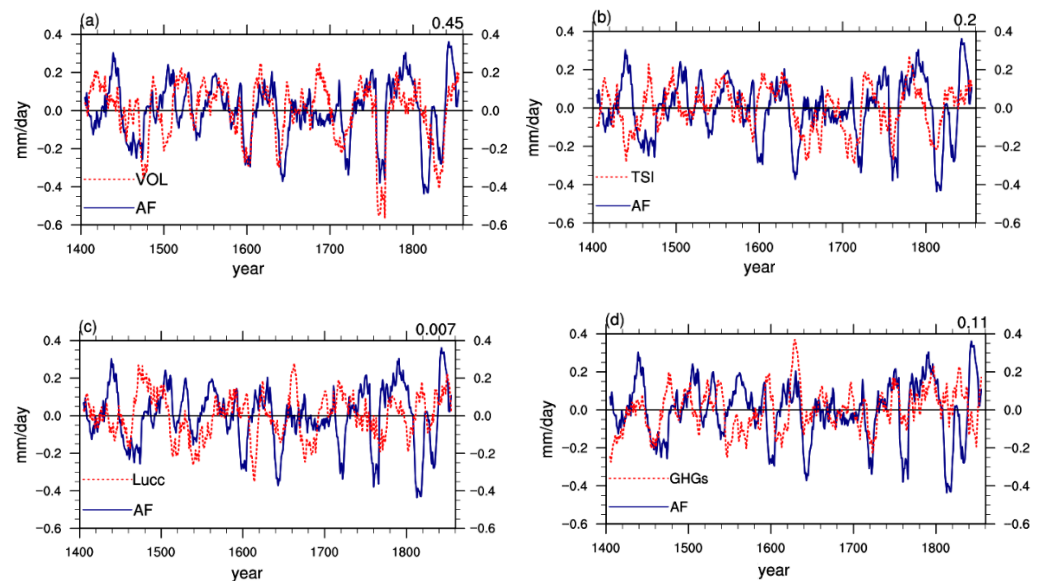


**Figure 6.** Correlation analysis between ISM precipitation under the AF experiment and Vol single-factor sensitivity experiments precipitation. The blue line represents the summer (JJAS) precipitation anomalies in India under the AF experiment, while the red dashed line represents the ISM precipitation anomalies under the single-factor sensitivity experiments: (a) Vol, (b) TSI, (c) LUCC, and (d) GHGs. All precipitation data were subjected to an 11-year moving average. The numbers in the upper right corner indicate the correlation coefficients between the AF precipitation and the precipitation from each single-factor experiment.

**Table 1.** Correlation analysis and significance level of solar irradiation experiment precipitation (TSI), volcanic experiment precipitation (Vol), greenhouse gas experiment precipitation (GHGs), land cover and land use experiment precipitation (LUCC), and AF experiment precipitation (AF).

| AF          | Vol         | LUCC       | TSI      | GHGs     |
|-------------|-------------|------------|----------|----------|
| correlation | 0.45 * (31) | 0.007 (36) | 0.2 (32) | 0.1 (36) |

\* Indicating statistical significance at the 95% level. The parentheses represent degrees of freedom.

A 56-year period in ISM precipitation during the LIA (1400–1860 CE) was identified through periodical analysis (Figure 7). Volcanic precipitation experiments show a period of approximately 56 years, which passes the 95% significance level test. Similarly to the research perspectives of other scholars [40,41]. The control experiment demonstrated the impact of internal variability within the climate system on climate change. Notably, precipitation in the control experiment lacked such a 56-year period, suggesting that the precipitation pattern was predominantly influenced by volcanic activity.

Figure 8 presents the correlations, significance levels, and degrees of freedom between precipitation in AF experiments during weak volcanic years (740–1200 CE) and precipitation from individual single-factor sensitivity experiments. The correlation coefficients between ISM precipitation (AF) and TSI, Vol, GHGs, and LUCC in the AF experiments were  $-0.19$  (28),  $0.14$  (27),  $0.024$  (32), and  $0.024$  (32), respectively. The correlation coefficient between volcanic-year precipitation and AF precipitation was  $0.14$ , with a significance level of  $0.48$  (Figure 8 and Table 2). This low correlation did not pass the 95% significance level test, indicating minimal influence of volcanic activity on ISM precipitation during volcanic years. Conversely, LIA volcanic activity had a significant impact on ISM precipitation, with a correlation coefficient reaching  $0.45$  and passing the 95% significance level test. These results suggest that ISM precipitation during the LIA was primarily influenced by volcanic activity.

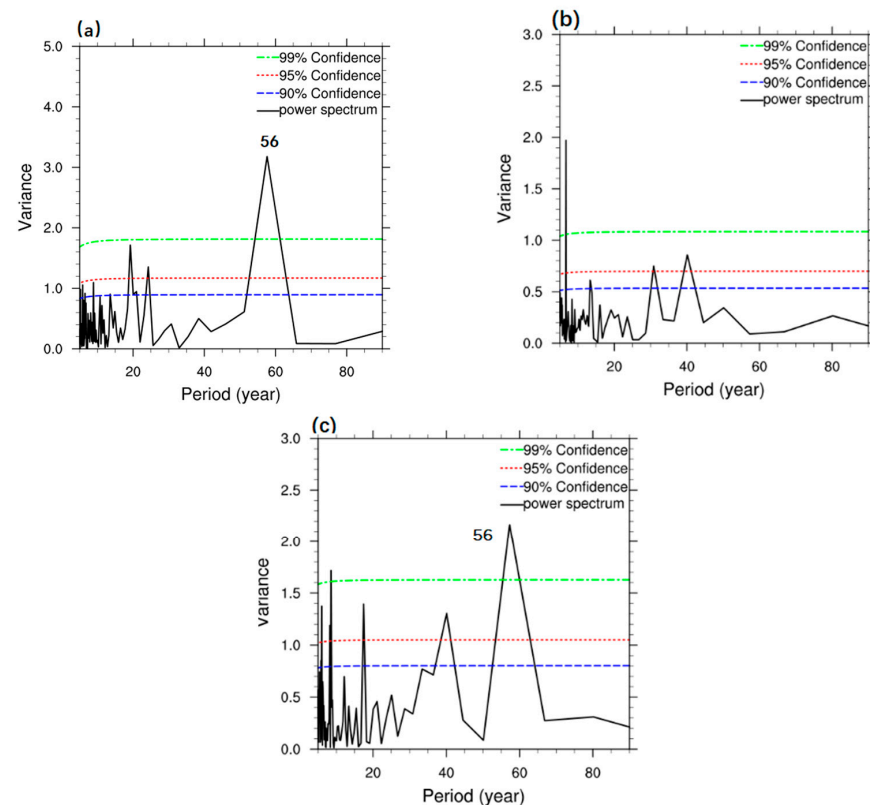


**Figure 7.** (a) AF experiment precipitation during the strong volcanic period (1400–1860), (b) Ctrl experiment precipitation, (c) Vol single-factor sensitivity experiment precipitation. Blue lines indicate significance at the 90% confidence level, red dashed lines indicate significance at the 95% confidence level, green dashed lines indicate significance at the 99% confidence level, and black solid lines represent the periodic variation in precipitation.

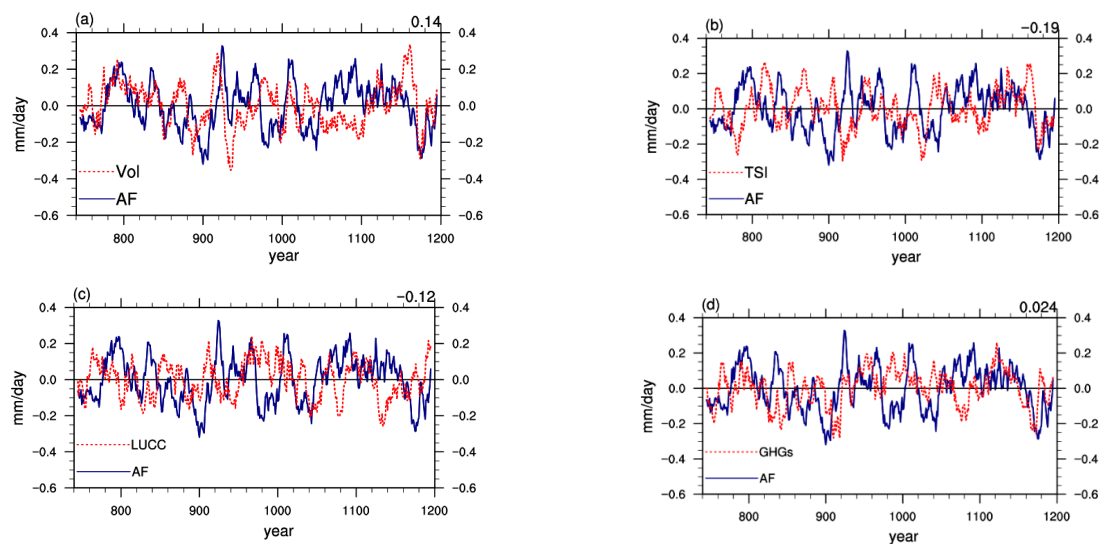


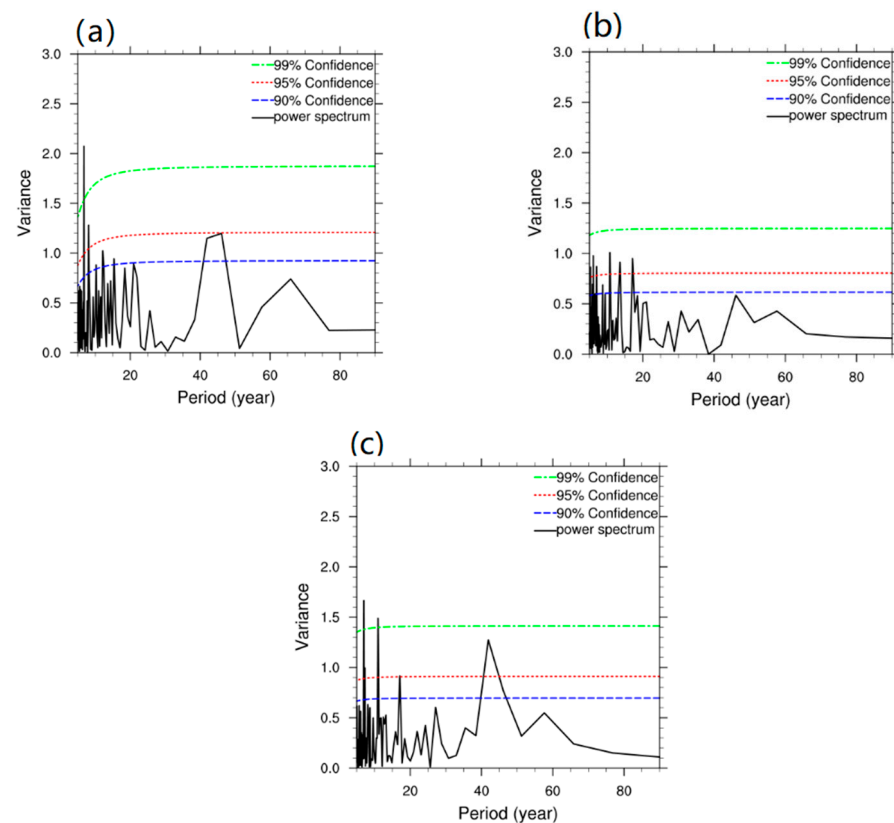
**Figure 8.** Correlation analysis between all-forcing experiment precipitation and single-factor experiment precipitation in weak volcanic years (740–1200). The blue line represents the ISM anomalies in India under the AF experiment, while the red dashed lines represent the ISM precipitation anomalies under the single-factor sensitivity experiments: (a) Vol, (b) TSI, (c) LUCC, and (d) GHGs. All precipitation data were subjected to an 11-year moving average. The numbers in the upper right corner indicate the correlation coefficients between ISM precipitation and precipitation from each single-factor experiment.

**Table 2.** Correlation analysis between single-factor experiments (TSI, Vol, GHGS, and land LUC) with ISM AF experiments precipitation.

| AF          | Vol       | LUCC       | TSI        | GHGS       |
|-------------|-----------|------------|------------|------------|
| correlation | 0.14 (27) | −0.12 (32) | −0.19 (28) | 0.024 (32) |

The parentheses represent degrees of freedom.

ISM precipitation showed a 45-year period that did not pass the 95% significance level test during weak volcanic years (740–1200 CE) (Figure 9). Volcanic activity triggered multidecadal variations in precipitation, with years of intense volcanic activity exhibiting approximately 56-year periodicity in ISM precipitation during the LIA. Reconstructed data has confirmed this roughly 56-year period. Years of weaker volcanic activity, however, did not show this pattern. Therefore, the 56-year period of ISM precipitation was affected by volcanic activity (Figure 7). In summary, the multidecadal variation characteristics of ISM precipitation during the LIA were primarily influenced by volcanic activity.

**Figure 9.** Weak volcanic years (740–1200): (a) AF experiment precipitation, (b) Ctrl experiment precipitation, (c) Vol experiment precipitation. Blue lines indicate significance at the 90% confidence level, red dashed lines indicate significance at the 95% confidence level, green dashed lines indicate significance at the 99% confidence level, and black solid lines represent the periodic variation in precipitation.

### 3.1.2. Attribution of Spatial Characteristics of Multidecadal Variation in ISM Precipitation During the LIA

In the spatial-scale analysis, the first mode of ISM precipitation is characterized by a tripartite spatial distribution extending from southwest to northeast, with two major precipitation centers: one near 18° N on the western side of the Indian Peninsula (Figure 10), and another in the southern waters of Myanmar, also around 16° N. The correlation coefficient between the ISM precipitation index and the PC1 component of the AF experiment EOF decomposition time series is 0.49 ( $p < 0.05$ ), indicating that both PC1 and the EOF decom-

position sequence of ISM precipitation effectively capture its spatial patterns (Figure 10). The second mode demonstrates a dipole spatial distribution extending from southwest to northeast, with a major precipitation center again near  $17^{\circ}$  N on the western side of the Indian Peninsula (Figure 10). The correlation coefficient between the precipitation index and the PC2 component of the AFEOF decomposition time series is 0.32 ( $p = 0.7$ ) (Figure 11), suggesting that the PC1 sequence reflects multidecadal variations in ISM precipitation, whereas the PC2 sequence fails to capture these patterns during the LIA.

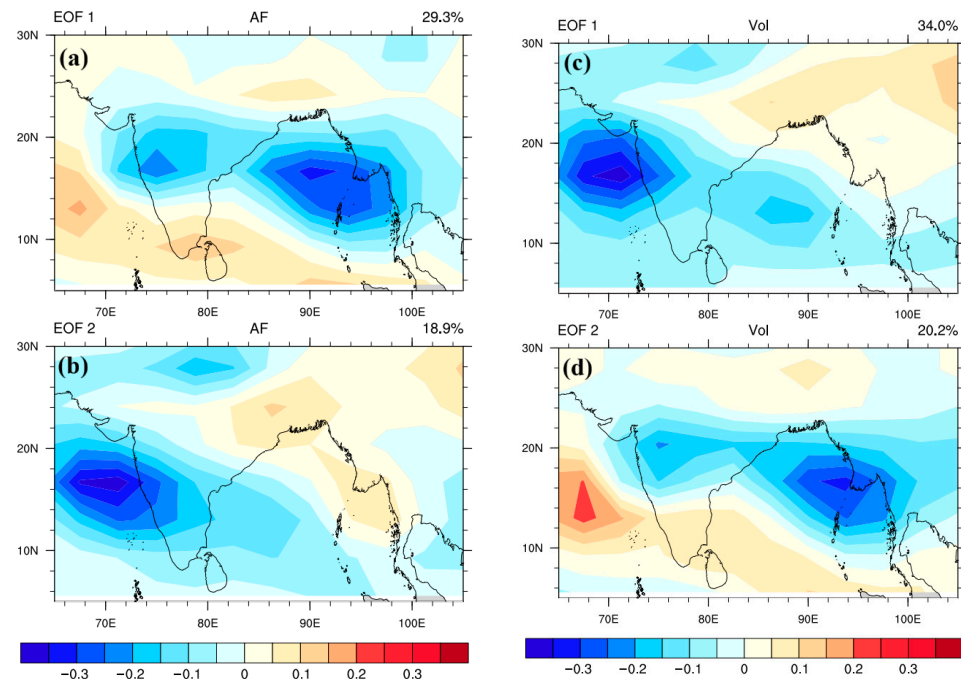


**Figure 10.** The empirical orthogonal function decomposition (EOF) pattern of Indian summer monsoon precipitation (JJAS) during 1400–1860, derived from the NNU-2K data, AF experiments showing the first (a) EOF1 and second (b) EOF2 spatial mode after an 11-year sliding average. Volcanic single-factor sensitivity experiments, showing the first EOF1 (c) and second EOF2 (d) spatial mode after an 11-year sliding average.

In the EOF decomposition of precipitation from volcanic activity experiments during the LIA, the first mode displays a dipole pattern extending from southwest to northeast. The second mode presents a triad pattern extending from southwest to northeast, with two major centers: one near  $18^{\circ}$  N west of the Indian Peninsula and another in the southern waters of Myanmar, also near  $16^{\circ}$  N. To spatially attribute ISM precipitation, precipitation fields from the AF experiment were first compared with those from the volcanic-forcing experiment using EOF analysis. The first mode of the AF precipitation EOF decomposition exhibited spatial consistency with the second mode of the volcanic-forcing precipitation EOF decomposition. Furthermore, the correlation coefficient between PC1 of the AF precipitation EOF decomposition time series and PC2 of the volcanic-forcing precipitation time series was 0.22 ( $p < 0.1$ , Figure 11b). Conversely, the correlation coefficient between PC2 of the AF precipitation EOF decomposition time series and PC1 of the volcanic-forcing EOF decomposition time series was  $-0.05$  ( $p = 0.8$ , Figure 10d). Therefore, the first mode of the AF precipitation experiment is influenced by the second mode of the volcanic precipitation experiment in terms of space. This reflects the spatial pattern of multidecadal variability of ISM precipitation during the LIA.

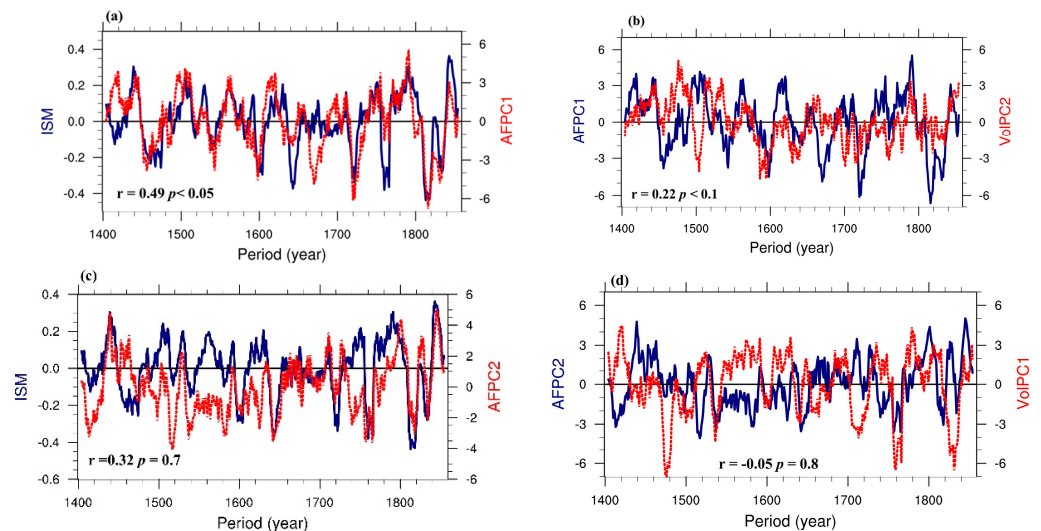


**Figure 11.** Correlation analysis between the ISM precipitation index and AF experiment precipitation EOF decomposition time series (AFPC1, AFPC2), as well as the correlation analysis between AFPC1, AFPC2, and Vol experiment precipitation EOF decomposition time series Vol (VolPC2, VolPC1). (a–c) Linear correlation analysis between the ISM precipitation index and the PC1 and PC2 time series of the AF experiment precipitation. (b–d) Linear correlation analysis between the PC2 and PC1 time series of volcanic experiment precipitation and the PC1 and PC2 time series of AF experiment precipitation. The ISM precipitation index was subjected to an 11-year moving average.  $r$  denotes the correlation coefficient, and  $p$  denotes the significance level.

### 3.2. Mechanism Analysis of Multidecadal Variation Characteristics of ISM Precipitation During the LIA

#### Influence of Land–Sea Thermal Difference Under Volcanic Activity on Multidecadal Variation Characteristics of ISM Precipitation

Massive volcanic eruptions are known to release substantial quantities of gases and volcanic ash. These emissions are transported into the atmosphere. Through the release of large quantities of aerosols, volcanic activity alters atmospheric composition and modifies global long-wave irradiation, short-wave irradiation, and latent heat flux. These processes ultimately result in changes in sea surface temperature (SST), which subsequently influence precipitation patterns through ocean–atmosphere interactions (Figure 12).

Under volcanic influence, SST underwent significant fluctuations. As a crucial driver of climate variability, SST fluctuations play a decisive role in shaping global monsoon precipitation patterns. Previous research indicates that fluctuations in North Pacific SST significantly influence the weakening or strengthening of Northern Hemisphere monsoons [42]. Cooling induced by volcanic activity in the Northern Hemisphere reduces the equatorial pressure gradient, which hinders the northward advection of low-pressure air from the western Pacific. This process leads to a weakened Northern Hemisphere and ISM, resulting in reduced precipitation across monsoon regions (Figure 13a). The thermal contrast between land and sea remains a key determinant of monsoon formation. ISM precipitation exhibits a significant correlation ( $r = 0.67$ ) with land–sea thermal contrast, validated at the 95% confidence level (Figure 14). Eurasia experienced pronounced cooling, whereas the Indian Ocean exhibited considerable warming (Figure 13b). The concurrent cooling of landmasses and warming of oceans impeded the advance of southwest monsoons into monsoon regions. The Intertropical Convergence Zone (ITCZ), a major persistent large-scale system in tropical regions, exerted a profound influence on weather variations across tropical and subtropical zones at multiple temporal scales. Its dynamic patterns are increasingly recognized as a primary driving force behind monsoon systems. The strength and position of the equatorial convergence zone profoundly influence ISM precipitation [43].

Through the AFPC1 regression of the volcanic single-factor sensitivity precipitation experiment, it can be found (Figure 13c) that there is a clear trend of precipitation reduction in the ISM region. Furthermore, the ITCZ displayed reduced precipitation, pronounced meridional gradient variations, and significant southward migration. These combined factors collectively contributed to reduced precipitation across the Indian subcontinent.

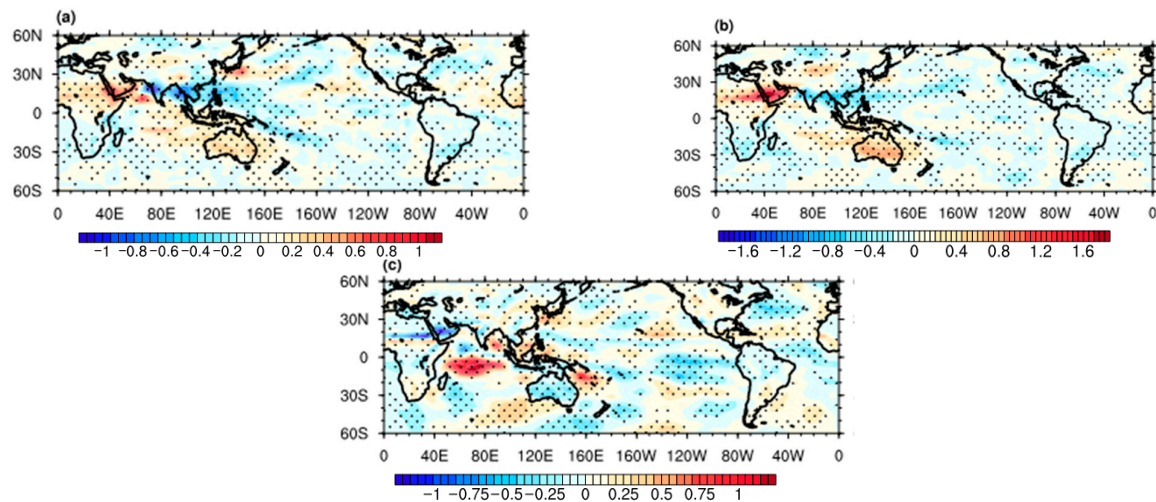


**Figure 12.** Regressed (a) shortwave irradiation (unit:  $\text{W}/\text{m}^2$ ), (b) longwave irradiation (unit:  $\text{W}/\text{m}^2$ ), and (c) latent heat flux (unit:  $\text{W}/\text{m}^2$ ) on the intrinsic time series PC2 from the EOF decomposition of precipitation from the LIA volcanic experiment. All variables were smoothed using an 11-year moving average, and the dotted areas indicate regions that passed the 95% significance level test.

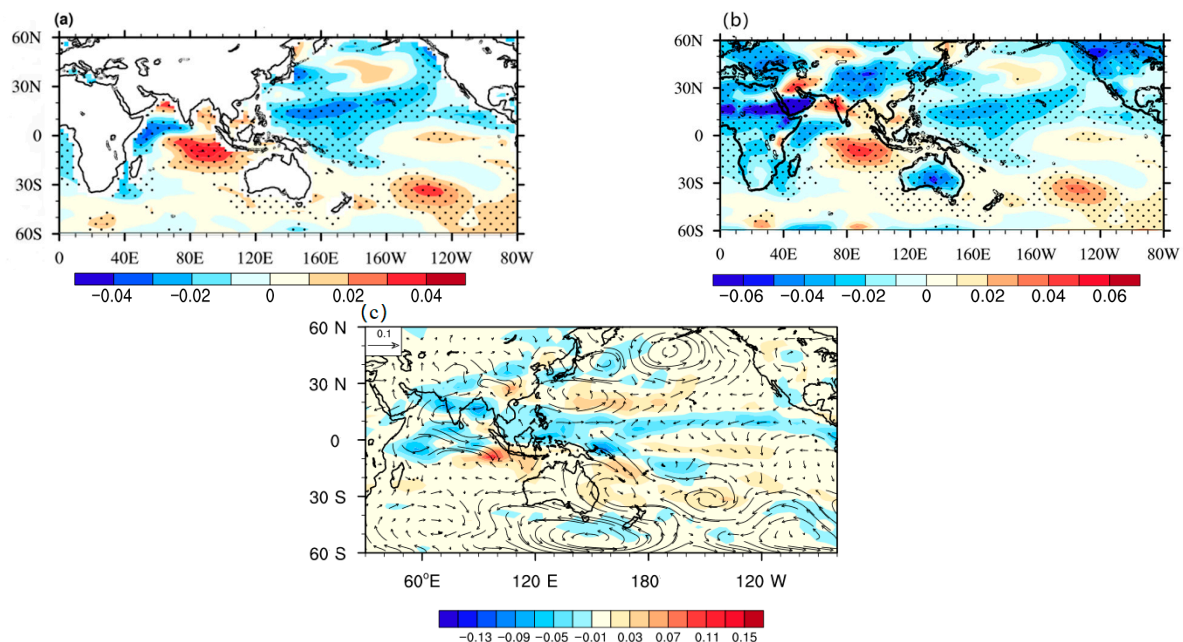


**Figure 13.** Analysis of the multidecadal causative mechanisms of ISM precipitation during the LIA. (a) Regression between the time series PC2 of the EOF decomposition of precipitation from the volcanic single-factor sensitivity experiment and the sea surface temperature field. (b) Regression field between the PC2 time series of precipitation EOF decomposition from the volcanic experiment and global surface air temperature. (c) Regression field between the PC1 of precipitation EOF decomposition from all-forcing and precipitation (shaded) experiments (units:  $\text{mm}/\text{day}$ ) and wind (vector) (units:  $\text{m}/\text{s}$ ) from the volcanic experiment. Dotted areas indicate regions passing the 95% significance level test. All variables were subjected to an 11-year moving average.

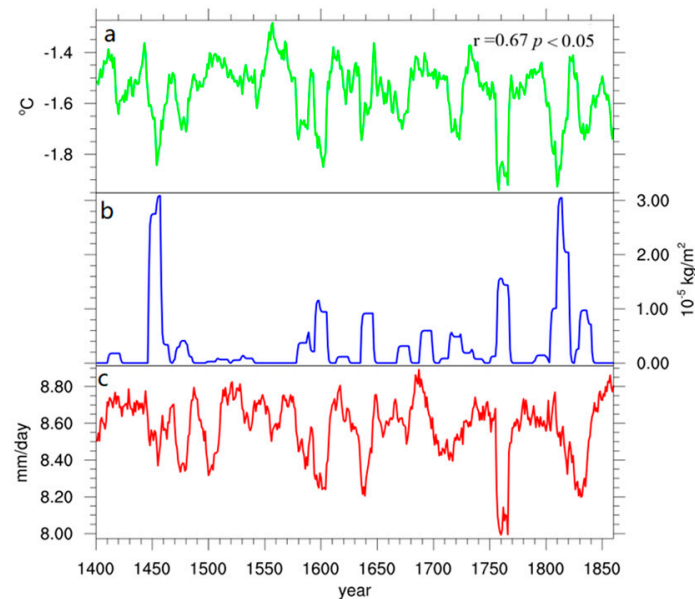


**Figure 14.** The primary factors controlling ISM precipitation during the LIA (1400–1860). (a) Multidecadal temperature time series of sea–land thermal contrast (JJAS) (unit: °C). (b) Volcanic external forcing series (unit:  $10^{-5} \text{ kg/m}^2$ ). (c) ISM precipitation (units: mm/day). To obtain multi-decadal signals, all variables were subjected to an 11-year moving average. The correlation coefficients and significance levels between the ISM index and the sea–land thermal contrast are shown in the upper right corner of the figure.

To examine the influence of atmospheric circulation on spatial variations in ISM precipitation, regression analysis was performed on the PC2 of precipitation time series decomposed by Empirical Orthogonal Function (EOF) under volcanic experiments, incorporating 850 hPa wind fields, full-layer water vapor flux, 500 hPa vertical velocity, and other variables (Figures 15 and 16). Analysis of the 850 hPa pressure and wind fields reveals that South Asia was affected by an anomalous anticyclone. On the one hand, elevated pressure over the monsoon region generated a distinct anticyclone center, leading to air divergence and subsidence. On the other hand, weakening of the Indian Ocean’s Mascarene High reduced the Somali Current, thereby diminishing southwest monsoon activity and hindering moisture transport into the monsoon region. Adequate moisture remained essential for precipitation formation. Regression fields between the PC2 of volcanic experiment precipitation EOF and 500–1000 hPa water vapor transport indicated elevated pressure over the Indian Peninsula and pronounced easterly winds, both of which hindered moisture transport into the monsoon region. Regression analysis of Vol experiments revealed a significant decrease in vertical water vapor velocity within the ISM region, further constraining precipitation formation. In conclusion, volcanic activity during the LIA exerted substantial influence on atmospheric circulation patterns in the ISM region. Under volcanic influence, the low-level wind field, water vapor transport, and vertical atmospheric motion in the ISM region were significantly altered. As a result, ISM precipitation decreased on multidecadal scales during the LIA.

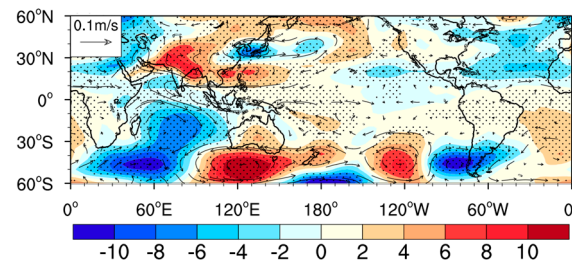


**Figure 15.** Regressed barometric pressure (shaded) (unit: hPa) and 850 hPa wind field (vector) (unit: m/s) on the intrinsic time series PC2 from the EOF decomposition of precipitation from the LIA volcanic experiment. All variables were smoothed using an 11-year moving average, and the dotted areas indicate regions that passed the 95% significance level test.

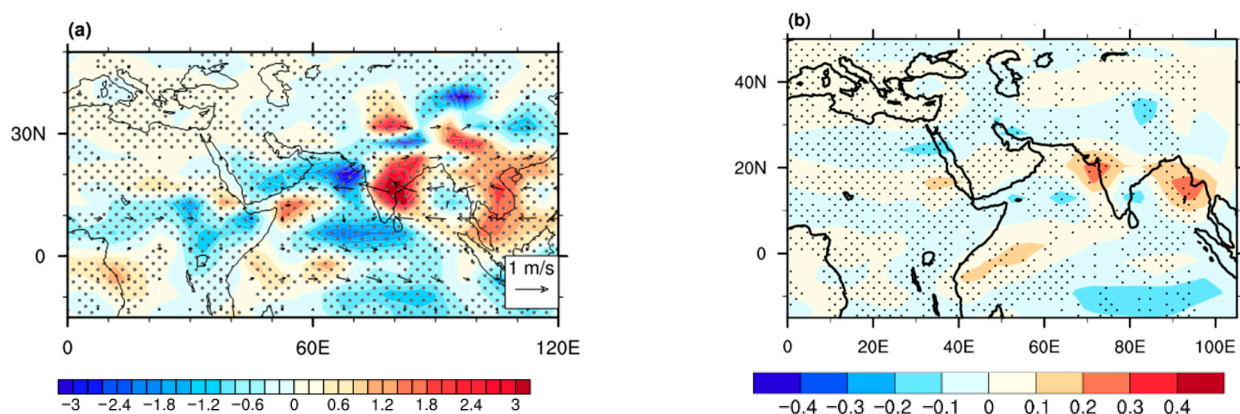


**Figure 16.** Regressed (a) 500 hPa vertical velocity (shaded) (unit: pa/s) and (b) 500 hPa to 1000 hPa water vapor transport (shaded) (unit: kg/m/s) on the intrinsic time series PC2 from the EOF decomposition of precipitation from the LIA volcanic experiment. All variables were smoothed using an 11-year moving average, and the dotted areas indicate regions that passed the 95% significance level test.

#### 4. Discussion

Although this paper analyzes the characteristics and causative mechanisms of multidecadal-scale variations in ISM precipitation during the LIA, the current conclusions may exhibit model dependency. Different models may respond differently to external forcings, potentially influencing the analytical results. Therefore, multi-model results should be employed for validation. There are studies indicating that solar radiation is also one of the factors affecting the LIA [44,45]. Volcanic eruptions release vast quantities of volcanic ash and aerosols into the troposphere and even the stratosphere, weakening solar radiation and acting as a sunshade. This subsequently triggers multidecadal variations in precipitation. The combined effects of volcanic activity, superimposed on solar activity minima, may have been one of the factors contributing to the LIA [46]. Future research should examine how solar radiation and volcanic activity interact to influence climate change during the LIA.

#### 5. Conclusions

This paper uses the CESM model simulation dataset (NNU-2K) to analyze the multi-decadal characteristics of ISM precipitation in the LIA, to examine its underlying mechanisms, and to derive the following main conclusions:

(1) A multidecadal pattern of precipitation changes was observed in the ISM region during the LIA. ISM precipitation was characterized by a notable 56-year period. Three sets of reconstructed data also reveal a roughly 56-year period. The multidecadal variation

pattern revealed a pronounced dipole distribution, characterized by a spatial transition from “positive” to “negative” phases extending from the southwestern to the northeastern regions. Two major precipitation centers were identified: one in the southern Bay of Bengal ( $15^{\circ}$ – $22^{\circ}$  N,  $86^{\circ}$ – $100^{\circ}$  E) and another over the western Indian Peninsula ( $17^{\circ}$ – $22^{\circ}$  N,  $71^{\circ}$ – $80^{\circ}$  E).

(2) To examine the role of volcanic activity, comparisons were made between weakly active years (740–1200) and strongly active years (1400–1860). Weak volcanic activity yielded only a correlation coefficient of 0.14 with the experimental precipitation, which did not pass the significance test. On the contrary, the relationship between the single-factor sensitivity experiment precipitation of strong volcanic years and the AF experiment precipitation is the highest, reaching 0.45 ( $p < 0.05$ ), and passes the test at a 95% significance level. It indicates that ISM precipitation during the LIA is mainly affected by volcanic activity. The Vol experiment precipitation revealed a 56-year period, whereas the control experiment did not exhibit such periodicity. This indicates that the 56-year period of ISM precipitation was primarily influenced by volcanic activity. Spatially, their spatial distribution patterns exhibited strong consistency. Consequently, the spatial distribution pattern of ISM precipitation during the LIA was also influenced by the second mode of the volcanic experiment precipitation, indicating two major centers: one on the western side of the Indian Peninsula and another in the southern waters of Myanmar.

(3) Volcanic activity induced a decline in SST in the northwestern Pacific Ocean during the LIA. The cooler North Pacific waters reduced the equatorial pressure gradient, thereby impeding the northward flow of low-level equatorial air currents. This weakening of the ISM led to a reduction in precipitation across the monsoon region. Simultaneously, Eurasia experienced cooling while the Indian Ocean warmed, creating unfavorable conditions for the southwest monsoon to penetrate the monsoon region. The reduction in precipitation in the equatorial convergence zone, accompanied by its marked southward shift, further contributed to diminished summer monsoon precipitation in India.

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