Hindawi
Advances in Meteorology
Volume 2023, Article ID 7256634, 12 pages
https://doi.org/10.1155/2023/7256634

Research Article

Orographic Effect and the Opposite Trend of Rainfall in Central Vietnam

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Received 19 July 2022; Revised 29 December 2022; Accepted 21 January 2023; Published 11 March 2023

Academic Editor: Hisayuki Kubota

Central Vietnam is characterized by severe flooding associated with heavy rainfall events caused by interactions between multiscale atmospheric circulations and the complex local terrain. Previous studies believed rainfall in central Vietnam is closely related to the cold surge; however, it fails to explain the cause of the early rainfall occurrence in August in the subregion. For the first time, this study investigates the detailed atmospheric mechanisms associated with rainfall variations in central Vietnam using the empirical orthogonal function (EOF) applied to the recently developed high-resolution Vietnam gridded precipitation (VnGP) dataset. Reanalysis data NCEP/NCAR is used to associate the rainfall changes with respective atmospheric mechanisms. EOF analysis detected two dominant rainfall modes. The primary mode explains the rainfall variation from October to November over the central and is directly related to the interaction of cold surges and tropical disturbances. The second mode accounts for rainfall occurring in north central from September to mid-October, which is attributed to the westerly summer monsoon activities. Also, we revealed that, while the first mode exhibits a significant correlation with El Niño-southern oscillation, the second depends highly on the contrast of sea surface temperature in the northern and southern Hemispheres. This different oceanic forcing and the local topological effect of Truong Son mountain range reasonably explain the opposite rainfall pattern in central Vietnam in early fall.

1. Introduction

Rainfall in Vietnam is characterized by distinct seasonal patterns among the country's climatic subregions [1–6]. In north and south Vietnam (Figure 1), significant rainfall is observed in the summer months (May–October), coinciding with the activities of the tropical westerly monsoon over these regions. In contrast, summer is a hot and dry season in central Vietnam. Previous studies [2, 7–9] emphasized that Truong Son mountain range, running along with the country, blocks low-level monsoon flows onto the windward side and causes the Foehn effect on the leeward side. Therefore, less rainfall is observed in central Vietnam in summer when the southwesterly wind prevails. The local rainy season begins in October when the northeasterly wind establishes and causes orographic rainfall on the eastern coast of Truong Son mountain range. Till December, the prevailing cold and dry northeasterly

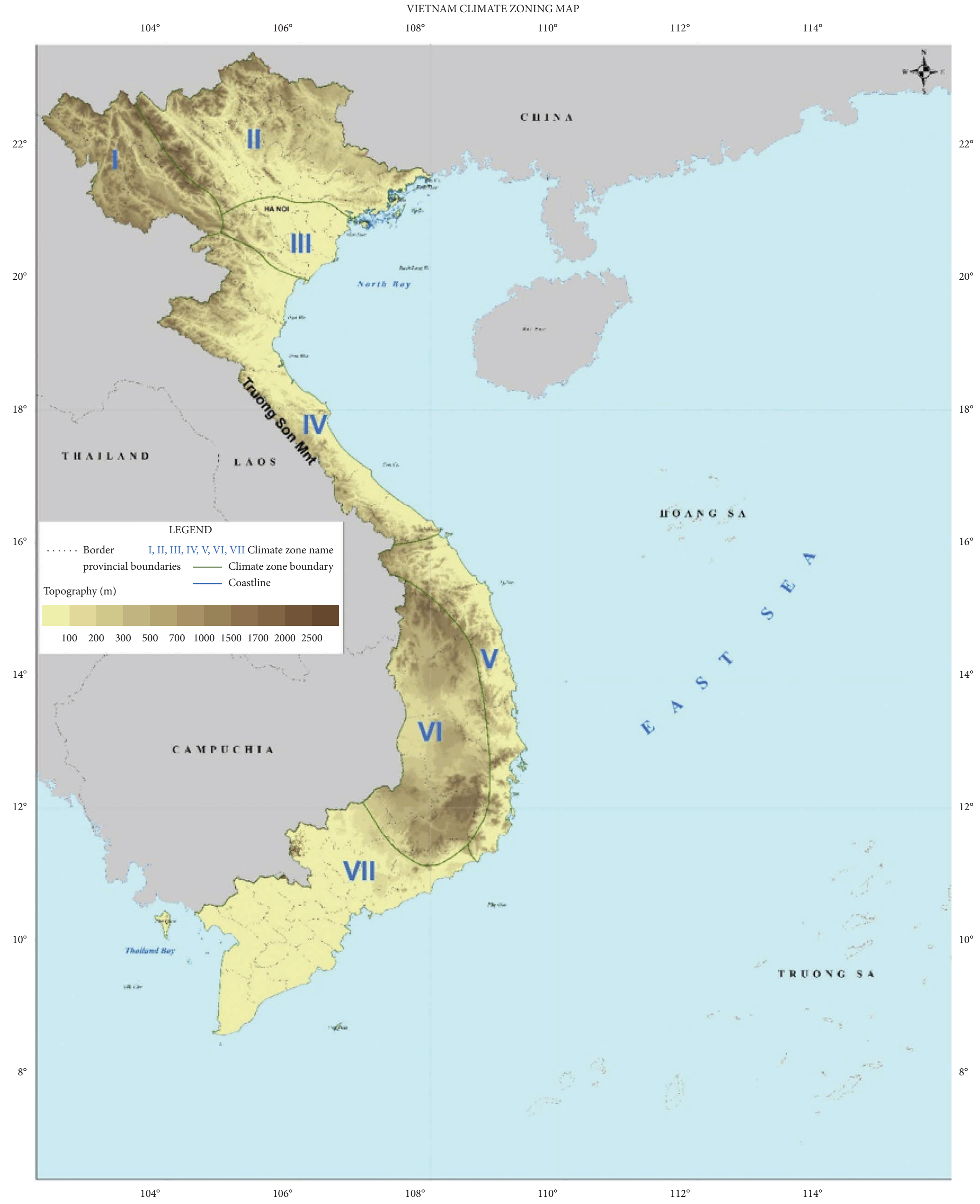


Figure 1: Topography height and seven Vietnam climatic subregions: Northwest (I), Northeast (II), Red River Delta (III), North Central (IV), South Central (V), Central Highland (VI), and Southern Plain (VII).

flows set up a highly stable environment and end the rainy season in central Vietnam [6–8, 10].

Central Vietnam frequently experiences heavy-rainfall-associated severe flood events, partly due to the complex local terrain. For example, the heavy rainfall event in November 1999 in Hue, one large city in the region, recorded a total rain amount exceeding 1800 mm for only two days. In another heavy rainfall event in October 2020, the monthly accumulations peaked at 3,245 mm in Huong Linh, Huong Hoa of Quang Tri province around October 20. Hundreds of people were killed and went missing after the floods hit the subregion. The disasters also caused enormous losses to agricultural production by destroying thousands of hectares of rice and vegetable crops. The infrastructure systems were also severely damaged. Therefore, the variations of rainfall in this subregion have been intensively studied (e.g., [7, 10–12].

Yokoi and Matsumoto [10] emphasized that the coupled effects of topography, stronger-than-usual northeasterly winds, and depression-type disturbance are the primary cause of heavy rainfall in November 1999 in central Vietnam. Composite analyses were also conducted and revealed that the coexistence of a cold surge and tropical depression is decisively important for forming heavy rainfall in the subregion. There is much less rainfall when a cold surge is not accompanied by a depression-type disturbance. Another study by Wu et al. [13] reported that heavy rainfall in central Vietnam tends to occur in strong phases of the Madden–Julian oscillation (MJO). While still considering the westward propagation of tropical depression from the western north Pacific (WNP) as the main cause of the heavy rainfall over the subregion, Wu et al. [13] argued that active phases of the MJO provided favorable conditions to maintain and intensify the disturbance. The possible mechanism of the intensification might relate to the enhancement of wave energy accumulation during the active phase of the MJO.

From the perspective of long-term variations, the fall rainfall in central Vietnam exhibits an apparent interannual variation that is in the opposite phase with the sea surface temperature (SST) in Niño-3.4 region (the correlation coefficient is −0.7) [7]. In cold years, defined as the years in which anomalous SST in Niño-3.4 region is −0.8 less than its standard deviation, the rainfall is much higher than that in warm years (when the SST in Niño-3.4 region is 0.8 greater than its standard deviation). These variabilities are primarily modulated by the changes in direction and intensity of large-scale water vapor flux in the WNP [7]. In warm years, the water vapor flux is stronger and directed more southeastward, which is nearly perpendicular to Truong Son mountain range. Under the orographic effect of the elevated terrain, the low-level flows are forced upward and cause heavy rainfall on the western slopes. In contrast, during warm years, the water vapor flux is weaker and almost parallel with the mountain range configuring an unfavorable environment for strong convection. Hence, less rainfall is induced in central Vietnam in these years.

The interannual variation of rainfall in central Vietnam is also explored in reference to severe weather activities [11]. It was emphasized that 62% of the total rainfall in central Vietnam is induced by heavy rainfall flood vortex (HRF vortex), which is much higher than that caused by cold surge vortex (CSV) and tropical cyclone (about 33%). In that study, the HRF vortex is distinguished from CSV by the occurrence of explosive cyclones in the north Pacific, and the maximum rainfall associated HRF vortex (CSV) is greater (lesser) than and equal to 200 mm per day. Therefore, the interannual variation of heavy rainfall in central Vietnam should be studied in terms of the interannual variation of the HRF vortex. However, while CSV and tropical cyclones landing in central Vietnam exhibit a clear contrast between warm and cold years, the population of the HRF vortex is not associated with the SST (Niño-3.4) index. As further explained by Chen et al. [11], in cold years, more water vapor is supplied to the HRF vortex by the environment; thus, the vortex could produce more rainfall than that in warm years.

Because cold surges and tropical cyclones were ascribed to the major forcing of rainfall in central Vietnam, the variations of rainfall in central Vietnam were mostly investigated in the period from October to November [1, 2, 4, 6, 7, 11]. However, the rainy season in central Vietnam literally starts from August, which is two months earlier than the prevailing of cold surge over the subregion. Surprisingly, the mechanism responsible for the early occurrence of rainfall in the subregion has received much less attention.

The present study is devoted to filling this study gap by exploring associated mechanisms causing the early rainfall occurrences in central Vietnam focusing on the roles of both synoptic circulations and the local terrain effect of the Truong Son mountain range. The empirical orthogonal function is employed on the recently developed high-resolution Vietnam gridded precipitation (VnGP) dataset to detect the rainfall patterns and cause attribution is conducted by linking the detected patterns to large-scale atmospheric mechanisms. Section 2 describes the data and methodology. The explanation for the early occurrence of rainfall and its interannual variability in central Vietnam are presented and discussed in Section 3. Finally, conclusions are given in Section 4.

2. Data and Methodology

2.1. Data. Vietnam gridded precipitation (VnGP) data at $0.25^{\circ} \times 0.25^{\circ}$ latitude–longitude resolution for 1980–2010 [14] are used in the present study. This dataset is constructed from rainfall observed at 481 stations across Vietnam based on the Spheremap interpolation technique. The data were validated for the spatial distribution, correlations, bias, and root mean square errors against gauge observations [14]. This is the first time the dataset is used to study the rainfall variation in central Vietnam. The resolution of VnGP allows one to investigate the detailed characteristics of rainfall in long and narrow central Vietnam.

Atmospheric data, which are used for cause attributions, are collected from reanalysis products. In detail, the wind and geopotential height are from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis [15]. The outgoing longwave radiation (OLR) data product from NCAR [16] and the monthly COBE sea surface temperature (SST) from the Japanese Meteorological Agency (JMA) [17] are used. The OLR and reanalysis data are at $2.5^{\circ} \times 2.5^{\circ}$ latitude-longitude resolution, and the monthly SST data are at $1^{\circ} \times 1^{\circ}$ latitude-longitude resolution.

2.2. Methodology. At first, the VnGP rain data, wind and potential height, and OLR datasets are smoothed by a 5-day running mean to remove the short-scale synoptic fluctuations. These are then subtracted to retain the data from September to November. To detect the trend of rainfall in central Vietnam, Sen's slope estimator [18] and Mann–Kendall [19] tests were used.

Sens' slope estimator (sometimes called the Thiel–Sen estimator), proposed by Theil and later expanded upon by Sen [18], is used to discover trends in univariate time series. The estimator is nonparametric, meaning that it is not based on a particular probability distribution. It is used as an alternative to the parametric least-squares regression, which uses a weighted mean to estimate the slope, but Sen's uses a median, which makes it resistant to outliers.

The Mann–Kendall (M-K) trend test analyzes monotonical (increasing or decreasing) trends in input time series. M–K is also a nonparametric test, i.e., free from a statistical distribution's assumption, except it requires no serial correlation in input data. M–K is a better alternative for simple linear regression when the data do follow a normal distribution, and the number of samples is few, though more data points are needed to find an actual trend (to avoid a chance).

The empirical orthogonal function (EOF) is applied to the reprocessed rainfall dataset to detect the subregion's principal rainfall modes (patterns) and how they change with time. Though it is not based on physical principles and the result might yield modes with mixed temporal signals [20], EOF is an effective method to recognize the regions (data points) with similar rainfall properties. Previous studies [5, 6] pointed out that EOF is a powerful tool for classifying rainfall patterns in Vietnam with reasonable physical interpretations for the corresponding patterns. Mathematically, EOFs are detected by computing the eigenvalues and eigenvectors of a field's spatially weighted anomaly covariance matrix. The eigenvalues are measures of the percent variance explained by each mode. Principal components (PCs) are determined by the associated temporal projection of eigenvectors, resulting in the amplitude of each mode over the period of record.

Finally, linear regression analysis (ordinary least-squares) is conducted to explore the relationship between historical rainfall changes (projected onto PCs) and large-scale circulation. Here, atmospheric variables such as OLR, wind, geopotential height, and SST anomalies are used as independent (predictor) variables, and PCs values are dependent (response) variables. A statistical hypothesis testing technique, *t*-test, was used to test the significance of the linear relationship between the response and predictor. In other words, it is used to determine whether there is a linear correlation between the response and predictor variables.

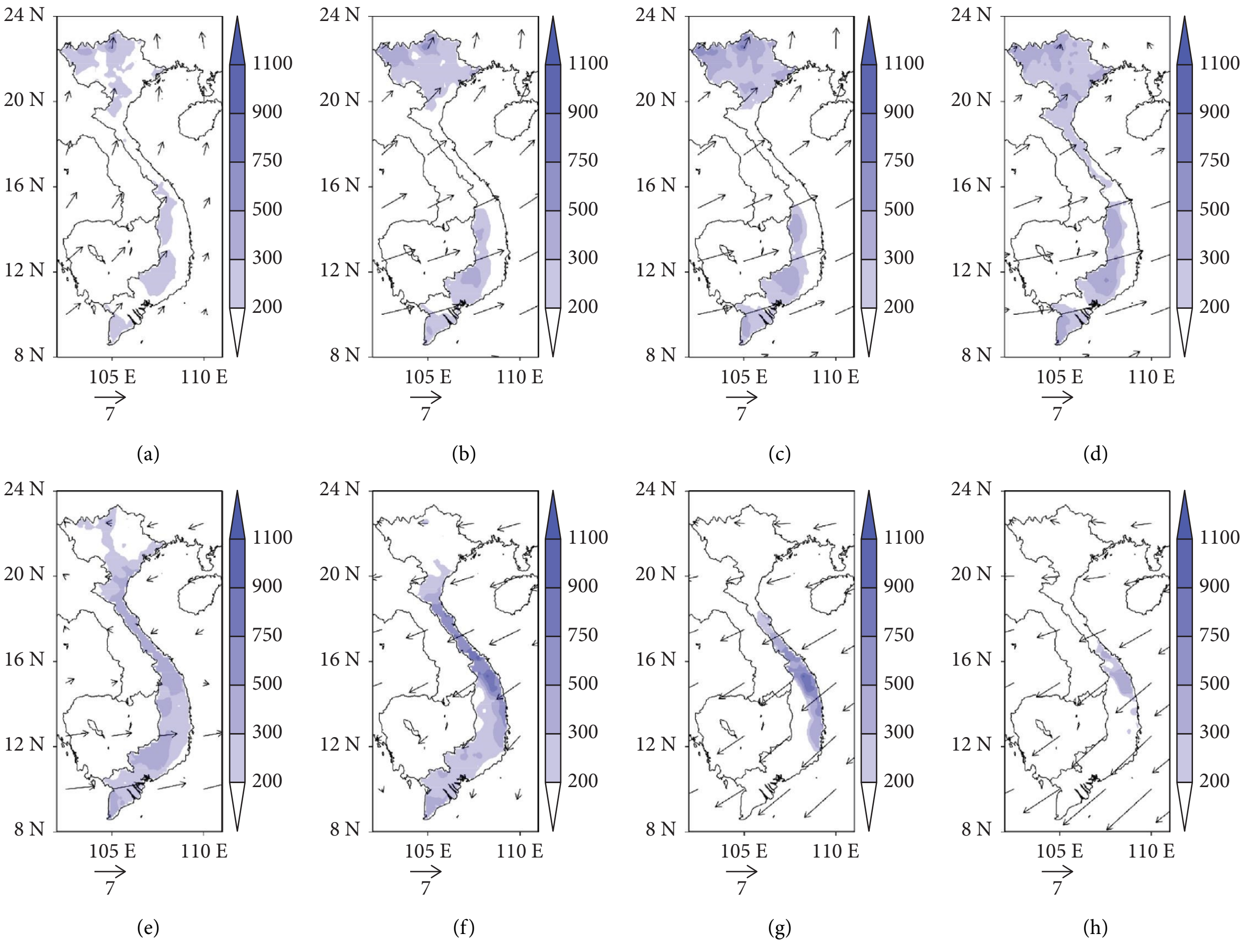
3. Results

3.1. Climatological Mean of Rainfall and Low-Level Wind. As displayed in Figure 2, rainfall is only observed in central highlands, northern, and southern Vietnam in boreal summer, which is chiefly associated with the prevailing westerly monsoon. Because the westerly wind is perpendicular to the Truong Son mountain range, the accompanied moisture is blocked by the mountain barrier. The consequent warm and hot wind, known as the Foehn effect, on the leeward side inhibits cloud formation, causing less rainfall in central Vietnam during summer. Satellite cloud observations well confirm the Foehn effect. We show a cloud image taken by satellite Himawari-8 (JMA, Meteorological Satellite Center of JMA) at 14 : 50 on 8 July 2019 in Figure 3 as an example, though a similar pattern can be seen on different dates also. One can see that cloud is highly concentrated on the windward side of the mountain range; meanwhile, the leeward side is totally free of clouds. This observation is consistent with arguments about the dry effect associated with the Foehn wind in Central Vietnam during summer in the previous studies [2, 6, 7, 10]. Especially, in June-July, rainfall is very low in the central region due to the influence of the Foehn effect [2]; rainfall is lower than 200 mm in the whole region (Figures 2(b) and 2(c)).

Significant rainfall starts occurring in north central in August with the monthly rainfall amount becoming greater than 200 mm (Figure 2(d)). The rainfall expands to the whole of central Vietnam in September and then reaches its maximum intensity in October (Figures 2(e) and 2(f)). In November, the rainfall starts decreasing and in December its footprint is noticed only over the middle parts of central Vietnam (Figures 2(g) and 2(h)). Since the rainfall generally appears in the transitional season when the low-level wind direction changes from westerly to northeasterly over the Gulf of Tokin, the northeasterly wind is ascribed to the advent of the rainy season in central Vietnam [1, 2, 6, 21]. The northeasterly wind blows over warm ocean water and brings rich moisture to supply the convections in the region. Under the orographic effect of Truong Son mountain range, the extratropical flows are pushed up and trigger terrain-induced rainfall.

At first glance, the temporal and spatial development of rainfall in central Vietnam is generally associated with the southward intrusion of the northeasterly winter monsoon. However, the northeasterly wind is not observed in the north central in August (Figure 2(e)), and the extratropical flows seem to be peculiarly weak in September (Figure 2(f)) to produce significant orographic rainfall in the central. The accordance of rainfall and the flows are only noticeable in October and November when the flows are strengthened significantly and blown perpendicularly to the coastal line of the subregion. Therefore, it raises a question about the role of northeasterly winter monsoons in inducing rainfall in central Vietnam in the early fall. There should be an additional mechanism that may not have been identified.

The Sen's slope of the fall rainfall in Vietnam is estimated (this is similar to those studies carried out by [22] and [23]). The Mann–Kendall test is also employed to examine the robustness of the results. It can be seen in Figure 4 that the negative Sen's slope values are clearly observed in north central and some parts of northern Vietnam from September to November, indicating the declination of rainfall in these subregions. The negative value of the Mann–Kendall statistic also displays a similar pattern to the negative Sen's slope values (Figure 4), indicating the convergence of the results with different methods. In contrast, the large positive Sen's slope values in midcentral and south-central reveal the increasing rainfall trend in these areas. However, this trend is not statistically significant according to the Mann–Kendall test (Figure 4). The contrast patterns of the rainfall between these two subregions again imply that there could be different processes constraining rains in the northern and southern parts of central Vietnam.



(a) (b) (c) (d)

(e) (f) (g) (h)

FIGURE 2: Climatological monthly mean of the VnGP rainfall (*shaded*, mm month^{-1}) and 925 hPa wind (*vector*, ms^{-1}) in the period of 1981–2010. (a) May. (b) June. (c) July. (d) August. (e) September. (f) October. (g) November. (h) December.

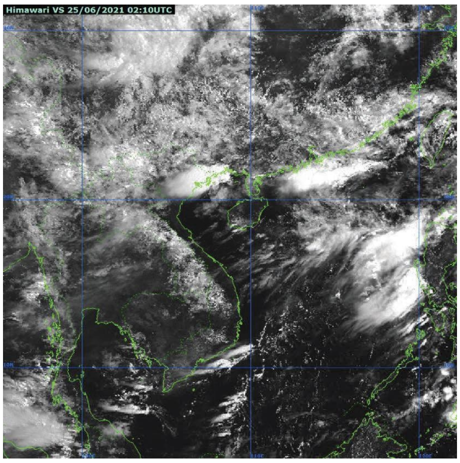


FIGURE 3: Cloud image (white color) at 14 : 10 25 june 2021 (source: Himawari-8).

Another major factor that contributes to the occurrence of rainfall in central Vietnam is tropical cyclones. However, according to previous studies [22, 24], the contribution of a tropical cyclone to the rainfall in north central in early fall is much less than that of nontropical cyclone rainfall. The ratio of tropical-cyclone-induced rain to total rain is less than 20% in September in the subregion. Therefore, tropical cyclone is not the dominant factor inducing rainfall in north central in the early fall.

3.2. *Leading Modes of Rainfall.*

To investigate the different mechanisms of rainfall in central Vietnam, EOF is applied to the rainfall from August to November. The variances explained by the first ten modes derived from the EOF analysis are plotted in Figure 5. It is clear that the first two modes, explaining for over 68.1% total variance of rainfall, are distinguished from the others. Thus, it is acceptable to retain the first two PCs from the EOF analyses. According to the rule of thumb proposed by North et al. [25], the sampling errors associated with the first two PCs are well separated; thus, these two first PCs should be considered individual subspaces, not a pair of eigenvectors.

The spatial patterns of the two EOFs are shown in Figure 6. The first EOF displays the positive value in the whole of central Vietnam with a clear core in the region of the middle part (Figure 6(a)). This pattern indicates that the positive phase of PC1 is characterized by the increase of rainfall in the whole of central Vietnam. Furthermore, the

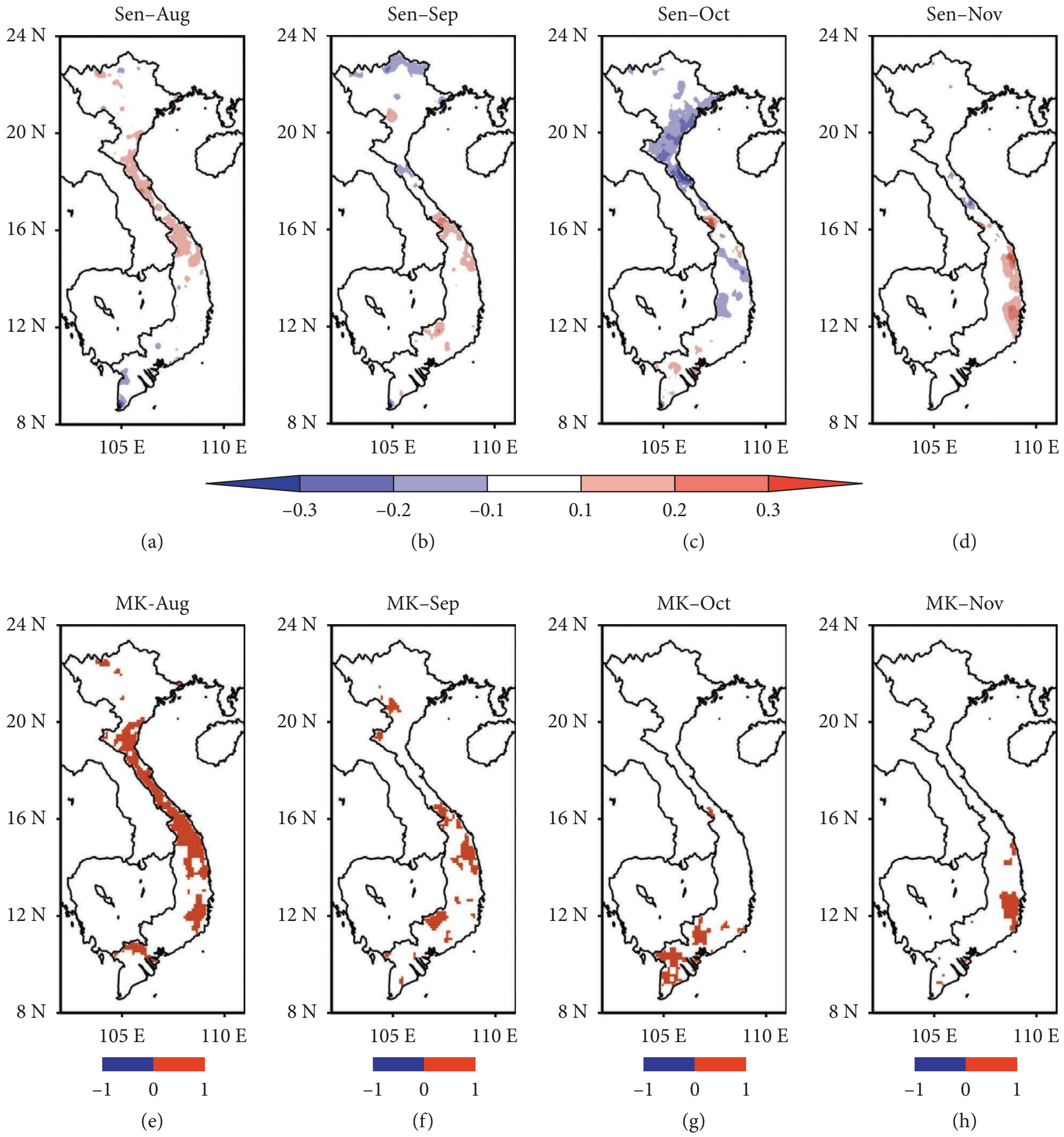


Figure 4: Sen's trends for the fall rainfall in Vietnam in the period of 1981–2010 (a–d) and the grid points satisfying significant statistic at the 90% level using the Mann-Kendall test (e–h). (a) Sen-Aug. (b) Sen-Sep. (c) Sen-Oct. (d) Sen-Nov. (e) MK-Aug. (f) MK-Sep. (g) MK-Oct. (h) MK-Nov.

EOF1 pattern significantly resembles that of the climatological mean of rainfall in October and November. Therefore, EOF1 might be associated with the wetter condition in central Vietnam from October to November. On the other hand, the second EOF displays a dipole pattern with positive values extending from the Red River Delta to a large part of north central and positive values cover most of south central (Figure 6(b)). This result implies that the positive phase of PC2 is associated with the raise of rainfall in north central and the fall of rainfall in south central. Therefore, EOF2 might account for the wetter condition in north central from August to October.

The temporal patterns of the two modes are also analyzed by examining their climatological mean. The values are the mean of the daily values of each PC in each year. As can be seen from Figure 7, PC1, from low values in August and September, goes up significantly in early October and then maintains at high values till late November. Therefore, PC1 is undoubtedly corresponding to the occurrence of the middle to late fall rainfall in the whole of central Vietnam. In a different manner, PC2 maintains at high values from August to September and then drops dramatically from the middle of October. Thus, the positive values of PC2 are associated with the increment of rainfall in north central from the early to the middle of fall. Therefore, the variations of rainfall in north central are simultaneously modulated by both EOFs. It is here that, from the middle of October to November, concurrent with the declinations of the two PCs, rainfall in the north central is substantially deceased. The consistency between the two EOFs and the variations of the rainfall indicate that the two EOF successfully clarify two physical modes of rainfall in central vietnam.

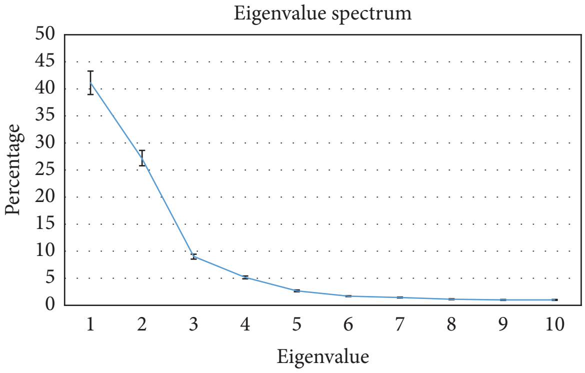
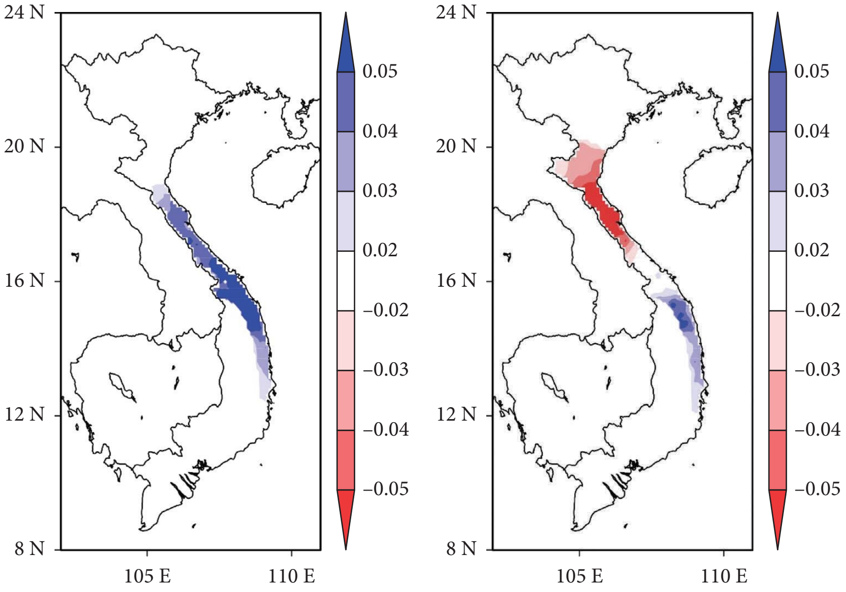


Figure 5: Variance percentages explained by eigenvalues of the first ten leading modes of the fall rainfall in Vietnam in the period of 1981–2010. The error bars display the sampling error at the 99% confidence level.



(a)

(b)

Figure 6: The First two EOF modes of the fall rainfall in Vietnam in the period of 1981–2010. (a) EOF1(41%). (b) EOF2(27.1%).

3.3. Associated with Anomalous Large-Scale Circulation and Orography Effect. The detailed mechanisms of rainfall in north and south central are further explored by associating large-scale circulations to two PCs (Figure 8). While both regression analysis and composite analysis are objective techniques which help to recognize the climatic pattern associated with each PC, we choose the former because the results are often smoother than that of the latter [26].

The regressed anomalous circulation pattern on PC1 is similar to the most well-known pattern inducing heavy rainfall in central vietnam (Figure 8(a)). In south central, a closed synoptic-scale anomalous negative pressure is evident, indicating the landfall of a tropical disturbance. At the same time, a large-scale anomalous positive pressure is observed over southern China and the northern part of Vietnam. As a result, the strong anomalous northwesterly wind is generated and directed to the eastern coast of Vietnam. This extratropical flow displaces the convergence of the pre-existing disturbance to the north and blows it into central Vietnam. Consequently, deep convection is induced, which is consistent with the negative value of OLR over the subregion. Therefore, PC1 corresponds to the rainfall caused by the cold surge and tropical disturbance interaction.

Because the activity of northeasterly cold surge is closely associated with the east Asian winter monsoon (EAWM); therefore, the large-scale circulation is also regressed on two EAWM indices to examine better the association of EAWM with rainfall in central Vietnam. The first EAWM index is based on the difference of 300 hPa zonal wind between (27.5–37.5°N, 110–170°E) and (50–60°N, 80–140°E), which represents the upper-level westerly jet over east Asia [27]. The second EAWM index is calculated by averaging 500 hPa geopotential height over the region (0–45°N, 125–145°E) [28]. One can see that the anomalous circulation patterns

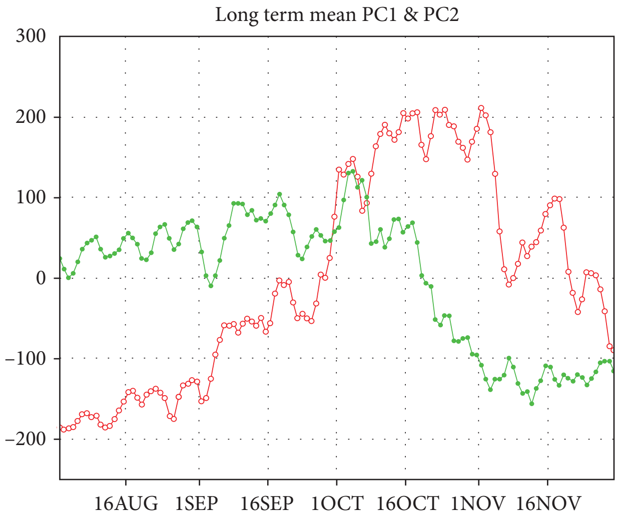
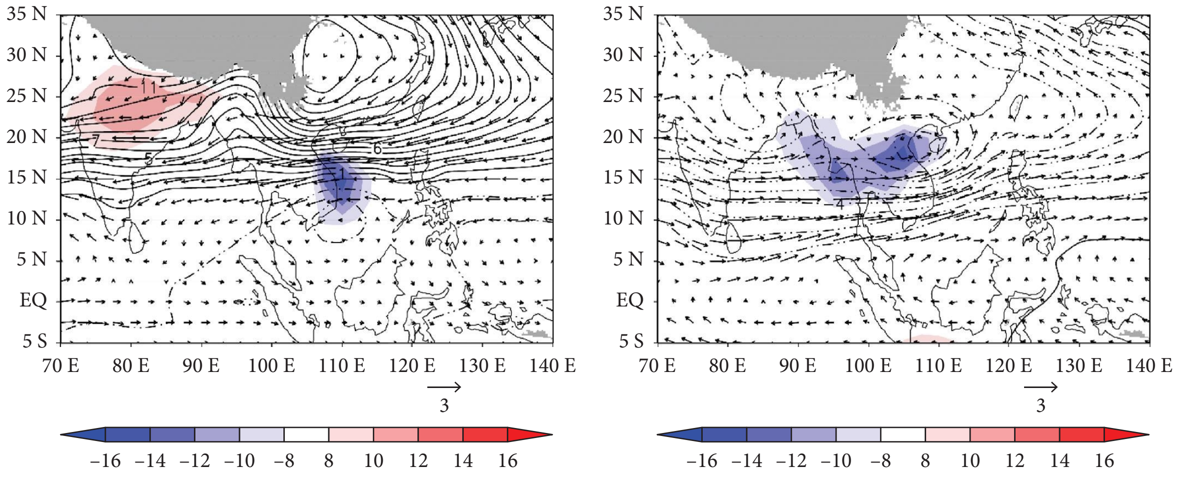


Figure 7: Climatological daily mean of the standardized PC1 (*red line*) and PC2 (*green line*) in the period of 1981–2010.



(a)

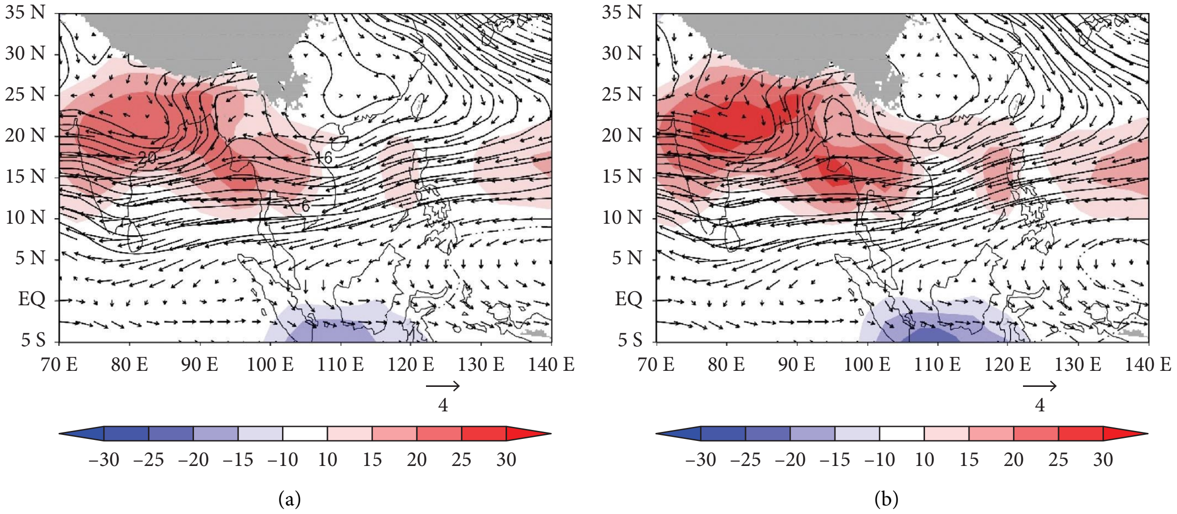
(b)

Figure 8: OLR (*shaded*, Wm^{-2}), 850 hPa wind (*vector*, ms^{-1}) and geopotential height (*contour*, m) anomalies regressed on the PC1 (a) and PC2 (b). (a) OLR,wind, hgt regreseed on PC1. (b) OLR,wind, hgt regressed on PC2.

regressed on the two EAWM indices also display the strengthening of northeasterly wind that is associated with the increase of geopotential height over southern China (Figure 9). Therefore, they resemble that is regressed on the PC1, which represents the southward intrusion of the cold surge.

The regressed circulation pattern on PC2 reveals a different mechanism of the early fall rainfall in north central (Figure 8(b)). It can be seen that there is a large-scale anomalous low pressure extending from northern India to north Vietnam, implying the deepening of the monsoon trough in these regions. To the south of the trough, the westerly monsoon is significantly strengthened due to the enhancement of the meridional pressure gradient. Concurrently, deep convection is clearly observed along the trough, displaying the strong correlation of monsoon circulation and convection. Therefore, PC2 is accompanied with the development of the westerly summer monsoon. It is noted that there is no signal of northeasterly flow in the regressed circulation pattern; thus, it does not contribute to the increment of early fall rainfall in north central.

It is emphasized in previous studies that Truong Son mountain range only plays the role of a natural barrier that prevents the westerly monsoon from inducing rainfall in central Vietnam [6–8]. However, the prevailing of the anomalous westerlies and deep convection over the Indochina peninsula (and central Vietnam) in Figure 8(b) tells another feature of the orography effect. In boreal summer, the low-level westerly wind is blown perpendicularly to the eastern side of Truong Son mountain range (Figure 2(a)); thus, only the air which is higher up near the mountain-top level could be able to pass over the lee slopes. The air then



(a)

(b)

FIGURE 9: Same as Figure 8 except for the 300 hPa zonal wind (a) and 500 hPa geopotential height indices (b). (a) OLR,wind, hgt regressed on U-index. (b) OLR,wind, hgt regressed on HGT-index.

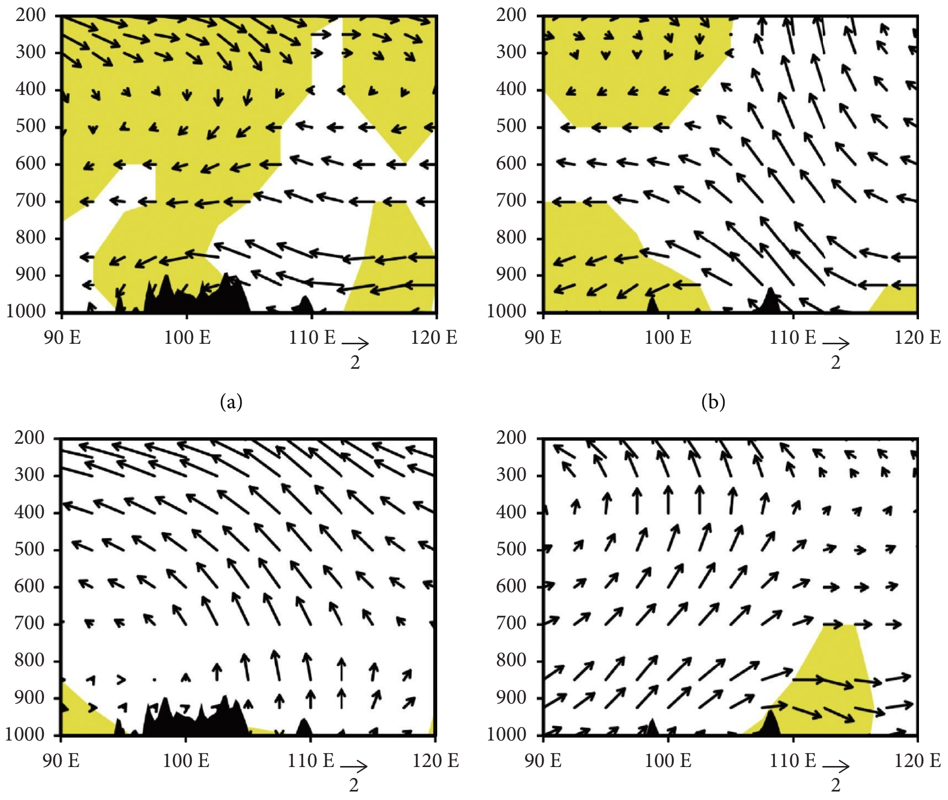
goes down as the Foehn wind becomes warmer and drier on the lee side after it is compressed. Therefore, the dry condition is generated in both north and south central. However, from August to September, the monsoon westerly flows are shifted to the south of 16°N (Figure 8(b)), and the associated descending motion is only maintained in South Central. Because the descending motion inhibits cloud formation, the dry condition only occurs in the subregion. In contrast, after passing the barrier mountain, the low-level flows turn into northeasterly and hits north central in the eastern coast. As the flows move across ocean water, rich moisture is transported to induce rainfall in the subregion. Consequently, under the effect of the Truong Son mountain range, the opposite pattern of rainfall is established in central Vietnam.

The different effects of the Truong Son mountain range on the large circulation are displayed through the vertical section of regressed circulation on the PC1 and PC2 (Figure 10). Since the PC1 corresponds to the rainfall produced by cold surges and tropical disturbances, the anomalous upward motion is observed in the eastern side of the mountain range at both the section of 19°N and 14°N (Figures 10(a) and 10(b)). As a result, rainfall is generated in both north and south central. This result is consistent with the EOF1 pattern where EOF values are nearly homogeneous over the whole of central vietnam. However, for PC2, the anomalous upward motion is only observed in the north central, indicating the orographic lifting on the summer monsoon circulation (Figure 10(c)). Meanwhile in south central, anomalous descending is induced, representing the Foehn phenomena (Figure 10(d)). Therefore, a contrast pattern of rainfall is established in central Vietnam that is consistent with the EOF2. This anomalous vertical section once again indicates that the interaction of summer monsoon flows and the Truong Son mountain range also significantly contribute to the rainfall variation in central Vietnam.

3.4. Oceanic Forcing and the Variations of the Two Rainfall Modes.

Variations of SST are considered the most important factor that modulates local rainfall and the associated circulation. To explore the relationship between SST and the rainfall in central Vietnam, the correlation coefficient patterns between the two modes and SST anomalies are displayed in Figure 11. For PC1, the pronounced negative coefficient is observed in the tropical center to the eastern Pacific, and the positive one is detected over the Maritime Continent, which resembles the pattern of La Nina in the mature phase (Figure 11(a)). These values are significant at a 95% confidence level, indicating that the late fall rainfall in central Vietnam tends to be higher (lower) in cold (warm) years. This result is in line with the previous studies [7, 11] that the late fall rainfall in central Vietnam occurs in the opposite phase of the Niño-3.4 region. As explained by Chen et al. [11], the large-scale environment in cold years supplies rich moisture for the disturbance to induce rainfall; therefore, much more rainfall is observed in central Vietnam in these years than in warm years.

In a different manner, PC2 also shows positive correlations with the SST over the northern hemisphere while high negative correlation coefficients are observed in the ocean in the southern hemisphere (Figure 11(b)). This result is in a good agreement with the notion that the Asian summer monsoon is principally modulated by the meridional thermal contrast [29, 30]. As higher SST in the northern hemisphere, more air is driven northward from the Indian Ocean. After crossing the equator, it becomes a southwesterly wind duo the Coriolis effect. The stronger monsoon winds mean more moisture is carried from the ocean and heavier rainfall is generated in north central. In contrast, the strong winds cross the Truong Son mountain and induce a severer Foehn effect in south central. Since the correlation pattern displays the contrast of SST in the northern and southern hemisphere, it can be understood the relationship of annual variation of rainfall and SST that follows the Sun.



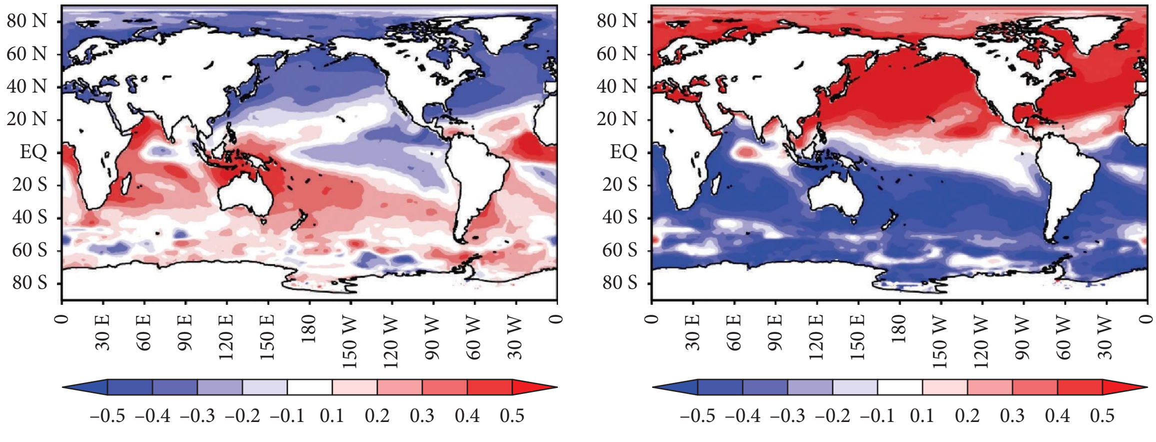
(a)

(b)

(c)

(d)

Figure 10: Vertical section of zonal wind (ms^{-1}) and vertical velocity (x 100 Pas^{-1}) across 19°N and 14°N regressed on the PC1 (a–b) and PC2 (c–d). The shaded areas indicate anomalous downward motion. (a) PC1, 19 N. (b) PC1, 14 N. (c) PC2, 19 N. (d) PC2, 14 N.



(a)

(b)

Figure 11: Correlation coefficient (*shaded*) between the SST anomalies and PC1 (a) and PC2 (b) in period of 1981–2010. (a) Coeff SST and PC1. (b) Coeff SST and PC2.

As the high-sun season moves southward, the SST drops (increase) in the northern (southern) hemisphere, leading to the decline of rainfall in central Vietnam.

4. Concluding Remarks and Discussion

The present study explores the different mechanisms of rainfall in central Vietnam. The most recent high-resolution VnGP dataset during the period of 1981–2010 is used within the EOF framework to detect the rainfall spatial variability patterns and their associated changes with time. Cause attribution is conducted by linking the rainfall variability with the large-scale atmospheric and oceanic circulation regimes. The major results are summarized as follows.

The rainfall in central Vietnam is characterized by the two dominant rainfall modes, which are derived from EOF analysis. By associating the two rainfall modes with large-scale patterns, this study, for the first time, reveals that rainfall in central Vietnam is not simply induced by the intrusion of the winter northeasterly flows. The first mode, which explains the rainfall variations from October to November in the whole region, is likely modulated by the combined effects of cold surges of tropical disturbance. The second mode, which demonstrates the fluctuations of rainfall from August to the middle of October in the north central subregion, is mostly induced by the extension of the monsoon trough from the north of India to the north of Vietnam.

The Truong Son mountain range plays a key role in inducing opposite rainfall patterns in North and South central vietnam. In boreal summer, the mountain barrier blocks the westerly wind on the windward side and creates dry conditions in the whole region of central Vietnam. From August to September, the monsoon trough moves to the south of 16°N and the prevailing westerly wind only dominates over the south central. Under the effect of the mountain range, the dry condition is still maintained in south central. The monsoonal flow then turns into the easterly wind that blows across the ocean water and brings rainfall to north central. Again, the mountain range plays an important role in triggering orographic rainfall in north central.

In addition, this study shows that while the fall rainfall in central Vietnam is modulated by ENSO, the early-fall rainfall in the subregion is controlled by the change SST on a global scale. It is in accordance with the theory that monsoons are the result of thermal contrast between the two hemispheres. However, the mechanism responsible for the opposite trend of rainfall variability in central Vietnam is still unknown. The decrease (increase) of rainfall in north (south) central is possibly related to the weakening of the Asian summer monsoon circulation. We suggest that the SST warming over the equatorial Indian Ocean reduces evaporation and diminishes the meridional SST gradient across the equatorial Indian Ocean, leading to the declination of the monsoon circulation. Further studies in this area are required to address this question.

Data Availability

The COBE SST data provided by the NOAA/OAR/ESRL PSL, Boulder, Colorado, USA, from their website at: https://psl.noaa.gov/data/gridded/data.cobe.html and original source at: https://ds.data.jma.go.jp/tcc/tcc/products/elnino/cobesst/cobe-sst.html. The reanalysis data archived at NOAA/PSL: https://psl.naa.gov/data/gridded/data.ncep.reanalysis.html.

Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the publication of this paper.

Acknowledgments

This study was supported by the project of "Characteristics of Trade Wind and its Influences on Weather and Climate of Vietnam" (Grant no. TNMT.2021.562.05), the project of "Advanced research in agricultural climate forecasting technology. Applied to forecasting agro-climatic conditions and impacts on rice production in the Red River Delta region" (Grant no. TNMT.2022.02.15), and the project of "Advanced research in technological innovation to forecast extreme cold, cold and heavy rain in the winter in the northern region of Vietnam with a lead-time of 10 days based on the operating rules of subtropical Jetstream" (Grant no. TNMT.2022.06.08).

References

[1] T. Nguyen Van, M. Nguyen Dang, K. Mai Van et al., "Climatic factors associated with heavy rainfall in northern Vietnam in boreal spring," *Advances in Meteorology*, vol. 2022, Article ID 5917729, 14 pages, 2022.

[2] N. Dang Mau, *Assessment and projection for the variability of Vietnam summer monsoon (VSM) characteristics*, PhD Thesis, Viet Nam Institute of Meteorology, Hydrology and Climate change (IMHEN), Hanoi, Vietnam, 2018.

[3] T. Vu Quoc, M. N. Dang, V. T. Nguyen, M. Tuan Bui, and T. H. Duong, "Large revelopment related to heavy principles in october 2020 in the central region," *Journal Of Climate Change Science*, vol. 20, 2022.

[4] D. Q. Nguyen, J. Renwick, and J. McGregor, "Variations of surface temperature and rainfall in Vietnam from 1971 to 2010," *International Journal of Climatology*, vol. 34, no. 1, pp. 249–264, 2014.

[5] B. M. Tuan, "Extratropical forcing of submonthly variations of rainfall in Vietnam," *Journal of Climate*, vol. 32, no. 8, pp. 2329–2348, 2019.

[6] D. Nguyen-Le, J. Matsumoto, and T. Ngo-Duc, "Onset of the rainy seasons in the eastern Indochina Peninsula," *Journal of Climate*, vol. 28, no. 14, pp. 5645–5666, 2015.

[7] M.-C. Yen and Coauthors, "Interannual variation of the rainfall in central Vietnam," *Journal of the Meteorological Society of Japan*, vol. 89, pp. 193–204, 2011.

[8] D. Nguyen-Le, J. Matsumoto, and T. Ngo-Duc, "Climatological onset date of summer monsoon in Vietnam," *International Journal of Climatology*, vol. 34, no. 11, pp. 3237–3250, 2014.

[9] D. M. Nguyen, M. Dang, and V. T. Nguyen, "Definition of new summer monsoon index for Vietnam region," *Vietnam Journal of Science, Technology and Engineering*, vol. 60, pp. 90–96, 2018.

[10] S. Yokoi and J. Matsumoto, "Collaborative effects of cold surge and tropical depression-type disturbance on heavy rainfall in central Vietnam," *Monthly Weather Review*, vol. 136, no. 9, pp. 3275–3287, 2008.

[11] T. Chen, J. Tsay, M. Yen, and J. Matsumoto, "Interannual variation of the late fall rainfall in central Vietnam," *Journal of Climate*, vol. 25, no. 1, pp. 392–413, 2012.

[12] N. Dang Mau, N. M. Truong, H. Sasaki, and I. Takayabu, "Rainfall projection for seasonal rainfall over Viet Nam by the end of 21st century under RCP8.5 scenario bythe nhrcm model," *Vietnam Journal Of Hydrometeorology*, vol. 673, pp. 7–13, 2017.

[13] P. Wu, Y. Fukutomi, and J. Matsumoto, "The impact of intraseasonal oscillations in the tropical atmosphere on the formation of extreme central Vietnam precipitation," *SOLA*, vol. 8, no. 0, pp. 57–60, 2012.

[14] T. Nguyen-Xuan, T. Ngo-Duc, H. Kamimera et al., “The Vietnam gridded precipitation (VnGP) dataset: construction and validation,” *SOLA*, vol. 12, no. 0, pp. 291–296, 2016.

[15] E. Kalnay, M. Kanamitsu, R. Kistler et al., “The NCEP/NCAR 40-year reanalysis project,” *Bulletin of the American Meteorological Society*, vol. 77, no. 3, pp. 437–471, 1996.

[16] B. Liebmann and C. A. Smith, “Description of a complete (interpolated) outgoing longwave radiation dataset,” *Bulletin of the American Meteorological Society*, vol. 77, pp. 1275–1277, 1996.

[17] M. Ishii, A. Shouji, S. Sugimoto, and T. Matsumoto, “Objective analyses of sea-surface temperature and marine meteorological variables for the 20th century using ICOADS and the kobe collection,” *International Journal of Climatology*, vol. 25, no. 7, pp. 865–879, 2005.

[18] P. K. Sen, “Estimates of the regression coefficient based on Kendall’s Tau,” *Journal of the American Statistical Association*, vol. 63, no. 324, pp. 1379–1389, 1968.

[19] M. G. Kendall, *Rank Correlation Methods*, Charles Griffin, London, UK, 1975.

[20] B. Wang and S.-I. An, “A method for detecting season-dependent modes of climate variability: S-EOF analysis,” *Geophysical Research Letters*, vol. 32, no. 15, Article ID L15710, 2005.

[21] D. N. Nguyen and T. H. Nguyen, *Climate and Climate Resources in Vietnam*, Agricultural Publishing House, Hanoi, Vietnam, 2004.

[22] H. Pham-Thanh, T. Ngo-Duc, J. Matsumoto, T. Phan-Van, and H. Vo-Van, “Rainfall trends in Vietnam and their associations with tropical cyclones during 1979–2019,” *Scientific online letters on the atmosphere: SOLA*, vol. 16, 2020.

[23] N. Endo, J. Matsumoto, and T. Lwin, “Trends in precipitation extremes over Southeast Asia,” *SOLA*, vol. 5, pp. 168–171, 2009.

[24] H. A. Nguyen-Thi, J. Matsumoto, T. Ngo-Duc, and N. Endo, “A climatological study of tropical cyclone rainfall in Vietnam,” *SOLA*, vol. 8, pp. 41–44, 2012.

[25] G. R. North, T. L. Bell, R. F. Cahalan, and F. J. Moeng, “Sampling errors in the estimation of empirical orthogonal functions,” *Monthly Weather Review*, vol. 110, no. 7, pp. 699–706, 1982.

[26] D. J. Lorenz and D. L. Hartmann, “The effect of the MJO on the North American monsoon,” *Journal of Climate*, vol. 19, no. 3, pp. 333–343, 2006.

[27] J. G. Jhun and E. J. Lee, “A new East Asian winter monsoon index and associated characteristics of the winter monsoon,” *Journal of Climate*, vol. 17, no. 4, pp. 711–726, 2004.

[28] S. Q. Sun and B. M. Sun, “The relationship between the anomalous winter monsoon circulation over East Asia and summer drought/flooding in the Yangtze and Huaihe River valley,” *Acta Meteorologica Sinica*, vol. 57, no. 4, pp. 513–522, 1995.

[29] P. J. Webster, V. O. Magaña, T. N. Palmer et al., “Monsoons: processes, predictability, and the prospects for prediction,” *Journal of Geophysical Research*, vol. 103, no. C7, pp. 14451–14510, 1998.

[30] D. H. McIntosh, *Atmospheric Science: An Introductory Survey*, Academic Press, New York, NY, USA, 1978.