CLIMATOLOGY, VARIABILITY, AND LARGE-SCALES INFLUENCE ON RAINY SEASON ONSET AND CESSATION OVER CENTRAL HIGHLANDS AND SOUTHERN VIETNAM DURING 1981–2019

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- Highlights:

- ✓ Rainfall-based criteria was used to detect rainy season onset (RSOD) and cessation (RSCD) from 1981 to 2019 across Central Highlands and Southern Vietnam.
- ✓ RSOD and RSCD occur earlier in the Central Highlands than in the Southern region.
- ✓ In both sub-regions, RSOD and RSCD have shifted earlier by approximately 5–7 days and 2–3 days per decade, respectively. El Niño delays onset and advances cessation, shortening the season, while La Niña has the opposite effect.

- Abstract: This study investigates the climatology, variability, and large-scale influences on the onset (RSOD) and cessation (RSCD) of the rainy season across the Central Highlands and Southern Vietnam during 1981–2019, based on daily rainfall data from 19 meteorological stations. A rainfall-based criterion was applied to determine RSOD and RSCD. The results indicate that the RSOD typically occurs earlier in the Central Highlands, around April 26, compared to the Southern region, where it occurs around May 8. This difference is largely attributed to orographic influences and the timing of southwest monsoon onset. Similarly, RSCD tends to occur earlier in the Central Highlands, approximately October 30, compared to around November 15 in the Southern region, likely due to the seasonal retreat of the Intertropical Convergence Zone (ITCZ). Interannual variability in both RSOD and RSCD ranges from 20 to 35 days, with higher variability observed in western and southwestern stations of Southern Vietnam, possibly influenced by fluctuations in summer monsoon intensity. Trend analysis indicates a shift toward earlier RSOD and RSCD at rates of approximately 5–7 days and 2–3 days per decade, respectively. Principal Component Analysis (PCA) reveals that the EOF1 explains 30% of the total variance in RSOD and 40% in RSCD. ENSO-related indices exhibit strong and statistically significant correlations with EOF1s, particularly for RSOD. El Niño

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events are generally associated with delayed onset and earlier cessation of the rainy season, resulting in a shorter duration, while La Niña tends to promote earlier onset and later cessation, thereby extending the season. These findings suggest that ENSO is a key large-scale climate driver and a potential predictor for seasonal forecasting frameworks of RSOD and RSCD in Vietnam.

- Keywords: *rainy season onset date; rainy season cessation date; Principal Component Analysis; ENSO, Central Highlands and Southern Vietnam.*

1. INTRODUCTION

Among rainfall-related characteristics, information on the onset and cessation dates of the rainy season (hereafter referred to as RSOD and RSCD) is crucial for several societal aspects [1], and especially for ecosystems [2]. In agriculture, knowledge of RSOD and RSCD variability supports optimal crop calendar planning, especially for rainfed systems. In water resource management, accurate forecasts of rainy season timing enhance reservoir operations, irrigation planning, and hydropower efficiency. These insights also contribute to disaster risk reduction by enabling local authorities to anticipate droughts or water shortages and take early action. Additionally, the timing and variability of the rainy season play a pivotal role in regulating Gross Primary Productivity (GPP), particularly in tropical ecosystems. Rainfall provides essential moisture that stimulate photosynthesis, leading to higher carbon uptake by vegetation. Changes in the onset and duration of the rainy season can significantly alter plant growth patterns and carbon fluxes. Thus, understanding rainy season dynamics is crucial for predicting GPP variability under current and future climate conditions [3].

Both RSOD and RSCD are commonly determined using specific criteria. Typically, rainfall-based approaches are applied at the local scale to identify RSOD/RSCD, while large-scale circulation-based methods are used at the regional scale. However, it is important to recognize the potential discrepancies between these two approaches, particularly in regions where the onset or cessation of the rainy season does not coincide with that of the monsoon. For instance, in the Central Highlands and Southern Vietnam, [4] observed that the onset of the rainy season may not correspond with the start of the summer monsoon. This finding aligns with the results of [5], who reported that the rainy season can begin approximately 2–3 weeks earlier than the monsoon onset in these areas. Therefore, circulation-based criteria for determining RSOD and RSCD in the Central Highlands and Southern Vietnam may not be appropriate for practical applications, particularly for end-users such as farmers, planners, or local authorities.

The temporal variability of the RSOD and RSCD, as well as the onset of the monsoon in many regions around the world, has been shown in numerous studies to be closely linked to ENSO. However, it is important to note that the impacts of these large-scale climate drivers on RSOD and RSCD vary across region. For instance, during El Niño years, the RSOD tends to start later in regions such as Indonesia [6,7], and Australia [8]. In contrast, in regions such as Tanzania and the Horn of Africa, El

Niño events are typically associated with an earlier onset of the rainy season and a delayed cessation of the short rains (e.g., the second rainy season), by about 7 days [9]. In the South China Sea region, [10] observed that the summer monsoon tends to begin later during periods of warming and earlier during periods of cooling in the Pacific and Indian Oceans. [11] showed that monsoons start later and are weaker during El Niño phases, and earlier with greater intensity during La Niña phases. [12] also confirmed this pattern, noting that El Niño years are typically associated with delayed monsoon onset and earlier cessation in Vietnam, while La Niña years show the opposite trend. Similar conclusions were pointed out by [13] for Southern Vietnam and by [14] for the Central Highlands. Furthermore, [15] emphasized that fluctuations in sea surface temperatures play a crucial role in modulating the timing of both the onset and end of the summer monsoon in these regions.

In Central Highlands and Southern Vietnam, despite the critical importance of RSOD and RSCD, most previous studies have primarily focused on RSOD, with relatively limited attention to the RSCD. Given recent findings that highlight notable shifts in the rainfall characteristics, including timing of monsoon onset and RSOD across Vietnam (e.g., [5, 16-20]), there is a demand to extend the investigation to include RSCD. Notably, the spatial distribution of trends in these characteristics varies significantly across stations and regions. This study addresses this gap by analyzing the spatial and temporal characteristics of both RSOD and RSCD, and by evaluating the influence of large-scale climate drivers over the Central Highlands and Southern Vietnam from 1981 to 2019. The outcomes are expected to offer valuable insights for identifying key predictors of rainy season variability, serving as a scientific foundation for the development of seasonal forecasting tools in Vietnam.

2. RESEARCH MATERIALS AND METHODOLOGY

2.1. Research materials

This study used the observed dataset over the 39-year period from 1981 to 2019 to examine the climatology, trends on the RSOD and RSCD over the Central Highlands and Southern Vietnam. Daily rainfall data were obtained from 19 meteorological stations gauges managed by the Vietnam Meteorological and Hydrological Administration (Table 1). To minimize the potential bias from missing data, monthly (annual) means were computed only when a station had data available for at least 25 days in a month (330 days in a year).

Table 1. List of 19 stations used in the study

No.	Station name	Longitude(°E)	Latitude(°N)	Sub-region
1	DAKTO	107.83	14.65	Central Highlands
2	KONTUM	108.00	14.33	
3	PLEIKU	108.02	13.97	

4	BUONHO	108.27	12.92	
5	EAKMAT	108.13	12.68	
6	BMTHUOT	108.05	12.67	
7	DAKNONG	107.68	12.00	
8	DALAT	108.45	11.95	
9	LIENKHUONG	108.38	11.75	
10	BAOLOC	107.82	11.53	
11	PHUQUOC	103.97	10.22	Southern Vietnam
12	RACHGIA	105.07	10.00	
13	CHAUDOC	105.13	10.70	
14	MOCHOA	105.93	10.78	
15	TAYNINH	106.12	11.33	
16	CAOLANH	105.63	10.47	
17	SOCTRANG	105.97	9.60	
18	VUNGTAU	107.08	10.37	
19	HAMTAN	107.77	10.68	

As mentioned in previous studies, large-scale atmospheric and oceanic processes significantly influence seasonal variations in Vietnam's weather patterns, including temperature [21], rainfall [22], and drought ([23,24]), heatwaves [25]. To identify key climate-related predictors for seasonal forecasting of RSOD and RSCD, 14 selected climate indices were averaged over different reference periods: for RSOD analysis, indices were averaged over the preceding December–January–February (DJF) season, while for RSCD, the averages were computed for the concurrent June–July–August (JJA) season. Detailed descriptions and time series of these indices are available at https://psl.noaa.gov/data/climateindices/list/.

2.2. Research methodology

2.2.1. Criteria for determination of RSOD and RSCD

As mentioned in previous studies, there are several criteria for determining RSOD and RSCD, which can be divided into two main groups: based on rainfall distribution and those related to the changes in atmospheric circulation. Thus, a rainfall-based approach from Stern et al. (1981) [26] is adopted to focus specifically on the temporal characteristics of RSOD. This criteria was applied in Central

Highlands of Vietnam ([14, 20]). In detail, the RSOD is defined as the first day of the year that satisfies the following conditions:

- Cumulative rainfall condition: The total rainfall over 5 consecutive days, starting from this day, must exceed 25 mm.
- Wet day condition: Within these 5 days, at least 3 days (including the RSOD) must record more than 0.1 mm of rainfall.
- Dry spell condition: In the 30 days following the RSOD, there must not be any period of more than 7 consecutive dry days (i.e., days with ≤0.1 mm rainfall).

To identify RSCD, the same rainfall-based criteria used for RSOD are applied in reverse, with the analysis proceeding backward from the end of the year using daily rainfall data.

After having determined the RSODs, the Sen's slope method [27] was used to estimate trends of RSOD. The statistical significance of trends at the 90% level was tested with the nonparametric Mann–Kendall test [28].

2.2.2. *The roles of large-scale climate drivers in RSOD and RSCD*

To explore the relationships between RSOD and RSCD characteristics in the Central Highlands and Southern Vietnam and large-scale climate drivers, Principal Component Analysis (PCA) is applied following the methodologies of [29] and [30]. In details, PCA is applied to identify the dominant spatial patterns (principal components, PCs) and their corresponding temporal variations (empirical orthogonal functions, EOFs) of RSOD and RSCD. Prior to the analysis, all input data were centered by removing the mean and standardized by dividing by the standard deviation at each station to ensure comparability across regions. Missing values, if present, were filled using the mean value of the corresponding station. Correlations between the EOF time series and 14 climate indices (listed in Table 3) are then assessed. Specifically, indices from the preceding December–January–February (DJF) season are used for RSOD, while indices from the concurrent June–July–August (JJA) season are used for RSCD. The implementation of the PCA technique follows the procedures described in [24] and [25]. Additionally, the North test [29] was applied to assess the statistical significance and independence of the empirical orthogonal functions (EOFs) derived from PCA. Specifically, it was used to determine whether the leading EOF modes of RSOD and RSCD are significantly separated from one another. Furthermore, spatial and temporal stability were further examined using varimax rotation and split-sample EOF analyses (1981–1999 vs. 2000–2019).

Besides that, the relationship between ENSO and RSOD/RSCD was also investigated. ENSO events are determined according to the Oceanic Niño Index (ONI), which is provided by the NOAA Climate Prediction Center (https://psl.noaa.gov/data/climateindices/list/). For RSOD analysis, ENSO phases are determined based on ONI values during the preceding DJF season, while for RSCD, ONI values from the concurrent JJA season are used. An event is defined as a warm (cold) ENSO event if the ONI value is higher (lower) than 0.5 K (−0.5 K). If the ONI value lies between 0.5 and−0.5 K, the event is referred to as an ENSO neutral event.

3. RESULTS

3.1. Spatial Distributions and Trends of RSOD and RSCD

As mentioned in the Introduction, there are several methods for determining RSOD and RSCD. To assess the effectiveness of our selected criteria, Figures 1 display the average monthly rainfall at each station within two sub-regions, along with box-and-whisker plots of RSODs and RSCDs based on the chosen criteria from 1981 to 2019. In general, the selected criteria accurately capture the seasonal rainfall patterns at most stations, with the onset and cessation months of the rainy season closely matching those from [31].

Figure 1 shows that the RSODs and RSCDs fluctuate between sub-regions and between stations within a sub-region. RSODs typically occur earlier in the Central Highlands compared to the Southern region, with the median climatological dates for RSODs being April 26 in the Central Highlands and May 8 in the Southern region. In the Central Highlands, the earliest onsets are observed in the southern part, including BAOLOC and DAKNONG generally around mid-April. The northern stations, such as KONTUM and PLEIKU, experience the onset later, around late April, while central locations like BMTHUOT see the latest onsets, usually in early May. In the Southern region, the rainy season begins earliest in the western and southwestern stations, such as TAYNINH, CHAUDOC, and RACHGIA, typically between late April and early May. Stations located in the eastern and northeastern parts of the Southern region, such as VUNGTAU and HAMTAN, experience the latest onsets, usually around mid-May. PHUQUOC stands out with the earliest onset of the rainy season, occurring around mid-April. Regarding RSCDs, the rainy season tends to end earlier in the Central Highlands than in the Southern region, with median climatological dates of October 30 and November 15, respectively.

Additionally, the interannual variability of RSODs and RSCDs varies significantly across stations in both the Central Highlands and Southern region, with values of IQRs ranging from commonly 20 to 35 days. In the Central Highlands, the IQR values for RSODs and RSCDs do not exhibit a clear pattern, possibly due to the combined effects of diverse orographic features and large-scale drivers during the transition period. In particular, the Central Highlands of Vietnam is a basaltic plateau surrounded by mountains. Its complex topography influences local rainfall by enhancing orographic lift in windward areas and causing rain shadows in leeward zones. This terrain could modulate the impact of large-scale climate drivers like the monsoon and ENSO, leading to varied rainy season timing across the region. In contrast, the Southern region shows greater interannual variability in both RSOD and RSCD at stations in the western and southwestern areas compared to those in the eastern and northeastern regions.

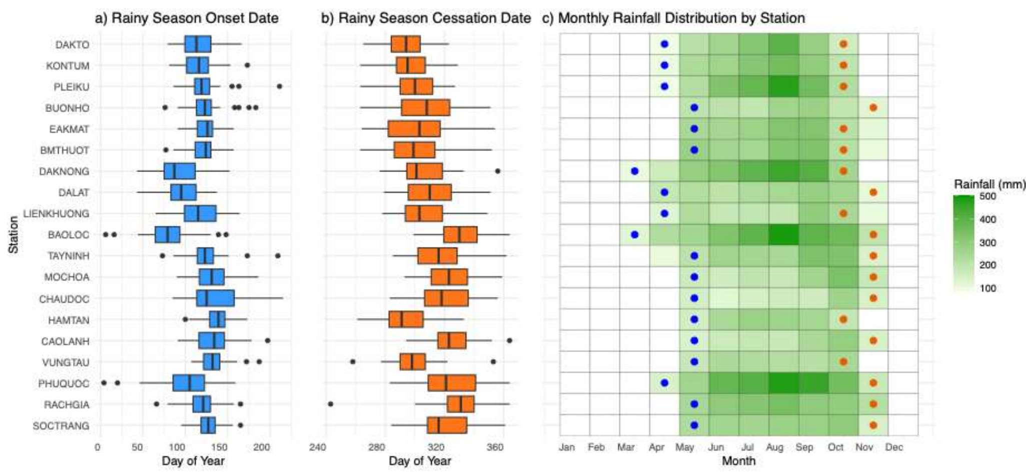

Figure 1. (a) Interannual variability of RSOD; (b) Interannual variability of RSCD; (c) Mean monthly rainfall with climatology month of RSOD (blue) and RSCD (orange) symbols.

In terms of trends, the rainy seasons in both the Central Highlands and Southern regions tend to occur earlier, about 5–7 days per decade. For the RSCD, the results indicate a trend toward earlier occurrence by approximately 2 to 3 days per decade.

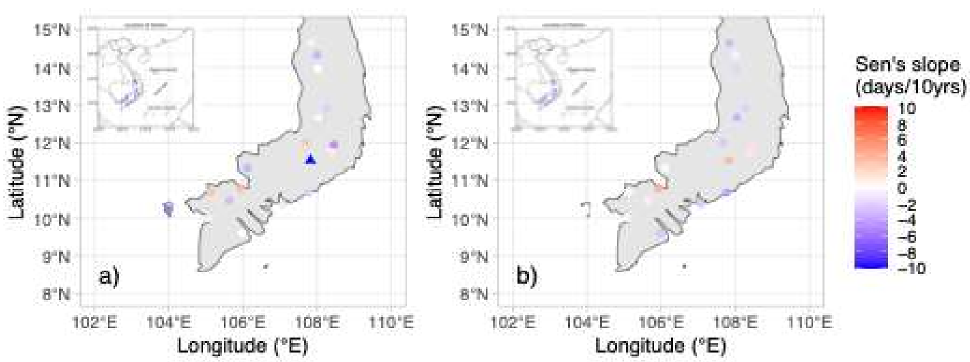

Figure 2. (a) Spatial patterns of trend of RSOD and (b) RSCD during 1981-2019. Triangle symbols indicate locations where the trends are statistically significant at the 90% confidence level, based on the nonparametric Mann–Kendall test.

3.2. Influences of large-scale climate drivers in RSOD and RSCD

Table 2 shows the proportion of cumulative variance explained by the first four principal components (PCs) of RSOD and RSCD. However, only the first of these components is statistically significant based on the North-test [32]. The first PC predominantly component accounts for approximately 30% and 40% of the total variance in RSOD and RSCD, respectively, while each of the remaining components explains less than 18%. In addition, the first PC demonstrates robust spatial and temporal stability, as confirmed by varimax rotation and split-sample EOF analyses (1981–1999 vs. 2000–2019; not shown). Therefore, only the first PC will be discussed in the following.

Table 2. Eigenvalues, explained variance and cumulative variance of the first four PCs.

	RSOD			RSCD		
	Eigen value	Variance (%)	Cumulative variance (%)	Eigen value	Variance (%)	Cumulative variance (%)
PC1	5.79	30	30	7.55	40	40
PC2	2.41	13	43	3.53	18	58
PC3	1.49	8	51	1.42	8	66
PC4	1.28	7	58	1.06	5	71

Overall, the spatial patterns of PC1 exhibit strong similarity between RSOD and RSCD, characterized by consistently high positive values across most stations within the study domain. Notably, approximately two-thirds of the stations display PC1 values greater than 0.55 (Figure 3). Given that PC values represent the correlations between the EOFs and the respective rainy season characteristics (e.g., RSOD and RSCD), the dominance of high PC1 values implies that EOF1 could serve as an indication of the temporal patterns observed in RSOD and RSCD.

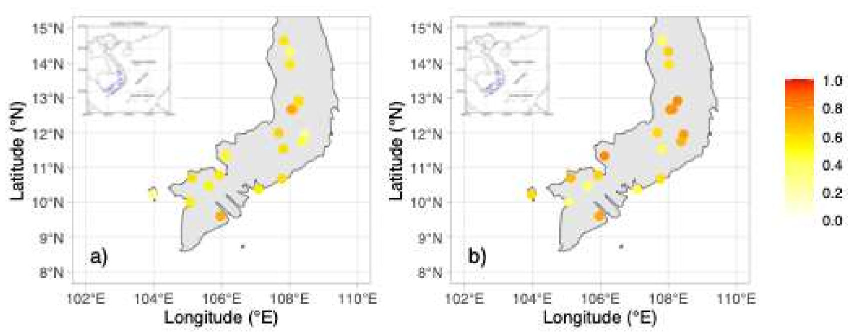

Figure 3. Spatial patterns of PC1 of (a) RSOD and (b) RSCD

Table 3 summarizes the correlation coefficients between 14 selected climate indices and the first empirical orthogonal function (EOF1) of both RSOD and RSCD. The results highlight a strong and statistically significant relationship at the 95% confidence level between ENSO-related indices (including NINO3.4, NINO4, ONI, CENSO, and SOI) and RSOD/RSCD characteristics. These indices exhibit strong correlations with RSOD, with absolute coefficients exceeding 0.7, whereas the absolute correlations with RSCD are generally weaker, around 0.35. However, the influences of ENSO on RSOD and RSCD are in contrast. In particularly, El Niño events are typically associated with later RSODs and earlier RSCDs, resulting in a shortened rainy season, while La Niña tends to produce earlier RSODs and delayed RSCDs, extending the season. Besides ENSO-related indices, other indices such as RINDO_SLPA, REQSOI, REPAC_SLPA, CPAC850, TNI, and MEI also show notable correlations with RSOD. These have been previously identified as contributing to ENSO evolution and its teleconnections, as noted in several studies (e.g., [33-37]). In contrast, climate indices like the Western Pacific Index (WP) and the Quasi-Biennial Oscillation (QBO) demonstrate negligible associations, with absolute correlation values below 0.1. Given that EOF1 accounts for over 30% of the variance in RSOD and 40% in RSCD, these findings reinforce the role of ENSO as the dominant large-scale driver shaping the timing of the rainy season across Central Highlands and Southern Vietnam.

Table 3. Correlation between climate indices and EOF1 of RSOD and RSCD. Positive and statistically significant values at the 95% confidence level of the t-test are highlighted in bold, and negative and statistically significant values at the 95% confidence level of the t-test are highlighted with bold and italic.

No	Acronym	Index Nam	PC1_RSOD	PC1_RSCD
1	NINO3	Eastern tropical Pacific SST (5N–5S, 150W–90W)	**0.67**	-0.21
2	NINO34	East Central Tropical Pacific SST	**0.74**	**-0.37**
3	NINO4	Central tropical Pacific SST (5N–5S, 160E–150W)	**0.75**	**-0.42**
4	ONI	Oceanic Niño Index	**0.75**	**-0.35**
5	CENSO	Bivariate ENSO Time Series	**0.72**	**-0.40**
6	MEI	Multivariate ENSO Index	**0.71**	**-0.34**
7	RINDO_SLPA	Equatorial SOI Indonesia SLP (standardized anomalies)	**0.74**	-0.06
8	SOI	Southern Oscillation Index	**-0.67**	**0.46**
9	REQSOI	Equatorial SOI (standardized anomalies)	**-0.76**	0.23
10	REPAC_SLPA	Equatorial eastern Pacific SLP (standardized anomalies)	**-0.64**	0.30
11	CPAC850	850 mb Trade Wind Index Central Pacific	**-0.72**	0.27
12	TNI	Trans-Niño Index	**-0.45**	0.29
13	QBO	Quasi-Biennial Oscillation	-0.04	-0.1
14	WP	Western Pacific Index	-0.1	-0.13

Figure 4 shows the spatial distribution of differences in RSOD and RSCD characteristics between El Niño and La Niña phases over the period 1981–2019. The influence of ENSO on RSOD is clear, with statistically significant differences at the 95% confidence level observed at more than half of the stations. On average, RSODs occur approximately 17 days later during El Niño years compared to La Niña years, with the most pronounced impacts observed in Southern Vietnam. In contrast, the effect of ENSO on RSCD is relatively weak, with only 2 out of 19 stations of the study domain showing statistically significant differences. Nevertheless, RSCDs tend to occur approximately 9 days earlier during El Niño phases compared to La Niña phases.

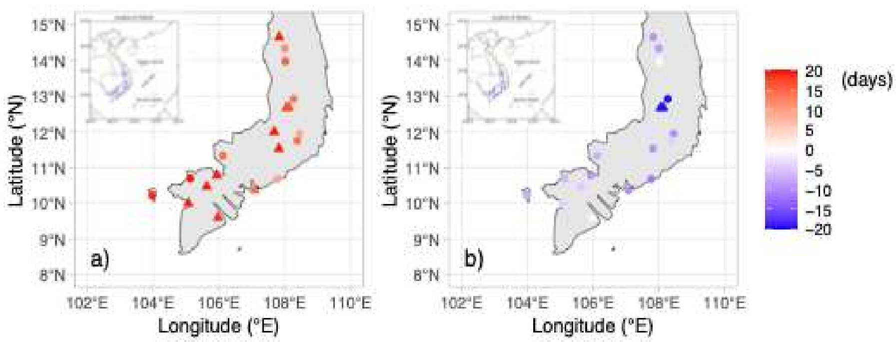

Figure 4. Spatial distribution of mean differences in (a) RSOD and (b) RSCD between El Niño and La Niña phases (1981–2019). Triangle symbols indicate stations where the mean differences are statistically significant at the 95% confidence level, based on t-test.

4. DISCUSSION

The RSODs and RSCDs fluctuate between sub-regions and between stations within a sub-region. Overall, RSODs typically occur earlier in the Central Highlands compared to the Southern region, with the median climatological dates for RSODs being April 26 in the Central Highlands and May 8 in the Southern region. Notably, within each region, spatial differences also exist. Specifically, in the Central Highlands, the earliest RSODs occur in the southern part of the region; likewise, in the Southern region, earlier RSODs are observed in western and southwestern stations. These local patterns could be influenced by the southwest monsoon and topographic features such as location, elevation and slope orientation. The spatial distribution of RSODs in the Southern region is likely influenced by its geographic location, which determines the timing of the arrival of southwest monsoon winds. Regarding RSCDs, the rainy season tends to end earlier in the Central Highlands than in the Southern region, with median climatological dates of October 30 and November 15, respectively. This could be related to the shifting of the Intertropical Convergence Zone (ITCZ) [31].

Besides that, results show the interannual variability of RSODs and RSCDs shows significant fluctuations across stations in both the Central Highlands and the Southern region, with values of IQRs ranging from commonly 20 to 35 days. In the Central Highlands, the IQR values for RSODs and RSCDs do not exhibit a clear pattern, possibly due to the combined effects of diverse orographic features and large-scale drivers during the transition period. In contrast, the Southern region shows greater interannual variability in both RSOD and RSCD at stations in the western and southwestern areas compared to those in the eastern and northeastern regions. This variability may be associated with the timing and intensity of southwest monsoon activity.

In terms of trends, the rainy seasons in both the Central Highlands and Southern regions tend to occur earlier, about 5–7 days per decade, consistent with findings from [5, 14 and 20]. Additionally, [19] observed that the monsoon onset dates in the Bay of Bengal, Indochina Peninsula, and western Pacific (around 120–140°E) have shifted 10–15 days earlier in recent decades, comparing the periods 1979–1993 and 1994–2008. For the RSCD, the results indicate a trend toward earlier occurrence by approximately 2 to 3 days per decade. These changes suggest a systematic shift in the timing of the rainy season across the region. However, understanding the causes of this shift will require further investigation within a broader climate change context, such as anthropogenic warming, land–atmosphere feedback, and regional circulation changes as key drivers of variability and trends in rainy season timing.

In this study, PCA revealed that only the PC1 of RSOD and RSCD was statistically significant according to the North-test, explaining approximately 30% and 40% of their total variances, respectively, while the remaining components each contributed less than 18%. The spatial pattern of PC1 was broadly consistent for both RSOD and RSCD, with high positive loadings across most stations. Correlation analysis between EOF1 and 14 climate indices indicated that ENSO-related indices (e.g., NINO3.4, NINO4, ONI, CENSO, SOI) exhibited the strongest and most significant relationships, particularly with RSOD, while correlations with RSCD were weaker. The influence of ENSO was opposite for RSOD and RSCD. In particular, El Niño years were associated with delayed onset and earlier cessation, resulting in a shorter rainy season, whereas La Niña years tended to produce earlier onset and later cessation, extending the season. These findings are consistent with previous studies [11, 15 and 38], which show that El Niño weakens the summer monsoon and suppresses rainfall over Southeast Asia, whereas La Niña enhances convection and strengthens monsoon winds. Other indices linked to ENSO evolution (RINDO_SLPA, REQSOI, REPAC_SLPA, CPAC850, TNI, MEI) also showed notable correlations, while WP and QBO had negligible impacts. Spatial analysis further confirmed that influence of ENSO on RSOD was significant across much of the domain, especially in Southern Vietnam, whereas its effect on RSCD was spatially limited. These findings underscore ENSO as the dominant large-scale driver of rainy season variability in the Central Highlands and Southern Vietnam.

5. CONCLUSION

Based on the data from 19 meteorological stations from 1981 to 2019, the results show that the selected criteria for identifying the RSOD and RSCD are effective in capturing both the seasonal and spatial variability of rainfall patterns across the Central Highlands and Southern regions. In particular, RSODs typically occur earlier in the Central Highlands compared to the Southern region, with the median climatological dates for RSODs being April 26 in the Central Highlands and May 8 in the Southern region, with clear intraregional variability that can be attributed to orographic effects and geographic positioning relative to the southwest monsoon. The rainy season tends to end earlier in the Central Highlands than in the Southern region, with median RSCDs around October 30 and November 15, respectively, which could be due to the seasonal transition of the ITCZ. Interannual variability in both RSODs and RSCDs ranges from 20 to 35 days, and tends to higher in the western and southwestern stations of Southern Vietnam, likely due to variations in the timing and intensity of southwest monsoon activity. Additionally, the results reveal that RSODs and RSCDs have shifted over the past four decades, with the onset and end of the rainy season occurring approximately 5–7 days and 2–3 days earlier per decade, respectively.

The results of applying the PCA method reveal that the first EOF1 captures the dominant mode of variability, accounting for 30% and 40% of the variance in RSOD and RSCD, respectively. The strong spatial coherence of PC1 suggests that it effectively represents the temporal structure of rainy season variability. Notably, ENSO-related indices, such as NINO3.4, ONI, and CENSO, exhibit significant correlations with EOF1, particularly for RSOD, indicating ENSO as a major driver of seasonal rainfall shifts. El Niño events are associated with delayed onsets and earlier cessations, shortening the rainy season, whereas La Niña conditions tend to extend it by prompting earlier onsets and delayed ends. In particular, ENSO's influence on RSOD is robust and statistically significant across much of the study area, especially in Southern Vietnam, with median delays of about 17 days during El Niño years. Although the impact on RSCD is weaker, a consistent tendency for earlier cessations during El Niño years is observed.

Therefore, although the data is limited to the 1981–2019 period, the lagged impact of ENSO on RSOD and RSCD is clear, suggesting the potential of using ENSO indices as key predictors for the timing of the rainy season Central Highlands and Southern Vietnam at seasonal timescale. However, further investigation into the underlying mechanisms and time-lagged effects of ENSO is necessary to enhance the accuracy and reliability of such forecasting systems.

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***Author contributions**: Dinh Ba Duy conceived the study and supervised its implementation. Pham Thanh Ha, Myslitskaia Natalia, Amirov Fedor, Pham Quang Nam, Ngo Thanh Dat, Dinh Vu Anh Tu, and Ha Quoc Manh were responsible for data processing. Dinh Ba Duy, Myslitskaia Natalia, Amirov Fedor, and Pham Thanh Ha contributed to data analysis, manuscript writing, and editing. All authors read and approved the final version of the manuscript.*

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