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Weather context in the Vietnamese Mekong Delta under the impacts of the typical ENSO phases

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सार – वैश्विक जलवायु परिवर्तन (जीसीसी) के प्रभाव के तहत, एल-नीनो और ला-नीना घटनाओं के कारण वर्षण की बदलती ऋतुनिष्ठ विशेषताओं ने दुनिया भर में चावल की खेती वाले क्षेत्रों (सीसीए) में फसल की पैदावार में गिरावट के संभावित जोखिमों को बढ़ा दिया है। यह अध्ययन विशिष्ट एल-नीनो और ला-नीना चरणों और वर्षण की ऋतुनिष्ठ विशेषताओं और वियतनामी मेकांग डेल्टा (वीएमडी) के भीतर सीसीए पर उनके बाद के प्रभाव के बीच संबंधों की जांच करता है।

1986 से 2022 तक 12 अवलोकन स्टेशनों से दैनिक वर्षा के आंकड़ों का विश्लेषण वीएमडी में ईएनएसओ घटनाओं और ऋतुनिष्ठ विशेषताओं के बीच संबंध की जांच करने के लिए किया गया था। परिणाम दर्शाते हैं कि एल-नीनो और ला-नीना घटनाएं वीएमडी में ऋतु विशेषताओं के समय और अवधि को महत्वपूर्ण रूप से प्रभावित करती हैं।

1999-2001 की अवधि में ला-नीना घटना के दौरान, वर्षा ऋतु आरंभ तिथि (RSOD) और वर्षा ऋतु अवसान तिथि (RSCD) दीर्घावधि औसत (1986-2022) की तुलना में क्रमशः तीन सप्ताह पहले और दो सप्ताह बाद हुई। इसके विपरीत, चरण 2014-2026 की चरम अल-नीनो घटना के दौरान, RSOD और RSCD में देरी हुई, जो दीर्घावधि औसत से 10.9 और 5.0 दिन बाद हुई जिससे पूरे VMD में वर्षा ऋतु की अवधि (LRS) 5.9 दिन कम हो गई। जीसीसी के तहत वर्षण की विशेषताओं में इन बदलावों ने VMD में खेती की गतिविधियों को प्रभावित किया। पाए गए निष्कर्षों से वीएमडी में चावल की खेती वाले क्षेत्रों की ईएनएसओ-संचालित जलवायु परिवर्तनशीलता के प्रति संवेदनशीलता पर जोर दिया गया तथा जीसीसी के नकारात्मक प्रभावों को कम करने के लिए अनुकूलन समाधानों को सक्रिय रूप से लागू करने के महत्व पर बल दिया गया है।

ABSTRACT. The shifting season features of precipitation due to the El-Niño and La-Nina events, under the impacts of global climate change (GCC), have increased the potential risks of crop yield decline in rice cultivation areas (CCAs) worldwide. This study examines the relationship between the typical El-Niño and La-Nina phases and the season features of precipitation, and their subsequent impact on CCAs within the Vietnamese Mekong Delta (VMD).

Daily rainfall data from 12 observation stations from 1986 to 2022 were analyzed to investigate the connection between ENSO events and season features across the VMD. The results indicate that the El-Niño and La-Nina events significantly influence the timing and duration of season features in the VMD.

During the La-Niña event in the period 1999-2001, the rainy season onset date (RSOD) and rainy season cessation date (RSCD) occurred three weeks earlier and two weeks later, respectively, than the long-term average (1986-2022). Conversely, during the extreme El-Niño event of the stage 2014-2026, the RSOD and RSCD were delayed, occurring 10.9 and 5.0 days later than the long-term average, with a shorter length of rainy season (LRS) by 5.9 days over the entire VMD. These shifts in the season features of precipitation under the GCC have impacted cultivation activities in the VMD. The findings underscore the vulnerability of rice cultivation regions in the VMD to ENSO-driven climate variability, emphasizing the importance of proactively implementing adaptation solutions to mitigate the negative impacts of GCC.

Key words – Crop yield, Drought, ENSO events, Precipitation, Salinity intrusion.

1. Introduction

Rainfall plays a pivotal role in determining crop sowing and harvesting dates (Lee and Dang, 2019; Nguyen *et al.*, 2022; Hu *et al.*, 2019). The variability in the RSOD, RSCD, and the LRS significantly impacts sowing schedules, crop growth, yield and food production (Bui and Dang, 2024; Bereket *et al.*, 2021; Cheria *et al.*, 2021). In the current background of GCC, the escalating intensity and frequency of droughts pose a critical challenge to maintaining irrigation resources (Azad *et al.*, 2022; Ferijal *et al.*, 2022; Fonseca *et al.*, 2022), especially considering the diminishing water resources from irrigation canals and rivers across the entire VMD, often referred to as the rice bowl of Vietnam (Nguyen *et al.*, 2022; Ngo and Le, 2025). Therefore, there is a pressing need to study the variability of rainfall features throughout the VMD (Bui and Dang, 2024; Lee and Dang, 2019). The rainy season stands out as the high concentrated period of precipitation in the VMD, accounting for up to 90% of the annual total precipitation (Nguyen *et al.*, 2022; Lee and Dang, 2019). Previous research has highlighted that El-Niño events lead to a deficit in rainfall in the VMD, resulting in extreme drought periods, such as those observed in 2014-2015 and 2019-2020.

During the early 21st century, large-scale extreme drought events, including severe droughts in 1990-1992, 2014-2015, and 2019-2020, have impacted the VMD (Nguyen *et al.*, 2022; Lee and Dang, 2019). Anomalies in rainfall patterns may stem from changes in large-scale circulation due to abnormal warming or cooling of the tropical Pacific (Rodrigues *et al.*, 2022; Wang *et al.*, 2004; Nguyen-Le *et al.*, 2015). The occurrence of such extreme weather and hydro-climate events has altered perceptions of climate extremes (Lee and Dang, 2019), with events labeled as "one-in-100-year events" due to their significant impacts on natural and human systems in the region, highlighting the growing vulnerability of the population and ecosystem to hydro-meteorological extremes (Nguyen *et al.*, 2022).

Studies indicate that the RSOD, RSCD, and the LRS, are undergoing significant changes under the influence of ENSO events (Dave, 2018; Faye *et al.*, 2022). Observations in the VMD reveal that the dry season has lengthened by approximately one month since the 1970s (Lee and Dang, 2019; Nguyen *et al.*, 2022). The dry season's duration has also altered notably with the presence of ENSO phases (Limsakul, 2019; Marengo *et al.*, 2011). For instance, during the recent El- Niño in 2015-16, rainfall in the VMD dropped below 200 mm of the long-term average, contributing to the most severe drought in 90 years across the entire VMD (Lee and Dang, 2019; Nguyen *et al.*, 2022). This shift in rainfall patterns has led to a decrease in the length of the rainy season and rainfall, closely linked to increased salinity intrusion in estuaries and its impact on rice cultivation in coastal areas (Omay *et al.*, 2023).

The shift in precipitation season features, including RSOD, RSCD and LRS, offer valuable insights for effective agricultural and water resource management (Bui and Dang, 2024; Panu and Kamphol, 2018). Accurately determining the RSOD and RSCD is crucial for understanding seasonal rainfall dynamics and their implications for water availability (Muñoz-Sanchez *et al.*, 2024; Pham and Phan, 2022). In the context of the VMD, where rice cultivation heavily relies on precipitation patterns, comprehending the dynamics of the rainy season is vital for farmers to make informed decisions regarding sowing and harvesting (Bui and Dang, 2024; Le and Ngo, 2025). The shifts in RSOD, LRS, and RSCD, potentially exacerbated by GCC (Marengo *et al.*, 2017; Moron and Robertson, 2014), underscore the need for assessment and adaptation solutions to mitigate their adverse effects (Li *et al.*, 2018; Misra *et al.*, 2023).Previous studies have highlighted the spatial and temporal variations in rainy season characteristics in Vietnam, emphasizing the necessity for comprehensive evaluations of their impacts on agriculture and water resource management (Bui and Dang, 2024; Dinh and Dang, 2021). Understanding the dynamics of the rainy season becomes imperative in a region renowned as Vietnam's rice bowl, where agricultural practices are deeply intertwined with seasonal rainfall patterns.

2. Data and methodology

2.1. *Study area description*

The VMD, situated in Southern Vietnam, is recognized as one of the primary delta regions in the country (Fig. 1). Spanning from 8°34' to 11°10'N latitude and 104°25' to 106°48'E longitude, this area covers the downstream segment of the Mekong River Basin (Dinh and Dang, 2021). With a total area of 40,577.6 km², it constitutes 12.8% of Vietnam's landmass (Lee and Dang, 2019). Home to a population of 17,744,947 individuals, the VMD plays a pivotal role in national rice production, contributing over 50% of the country's total output (Lee and Dang, 2019; Nguyen *et al.*, 2022).

The region boasts advantageous geographical characteristics, including abundant freshwater for agriculture, nutrient-rich sediments transported from the upstream Mekong River, and significant local precipitation (Lee and Dang, 2019). The rainy season in the VMD is primarily shaped by the Southwest monsoon (Bui and Dang, 2024). Rainfall gradually increases from

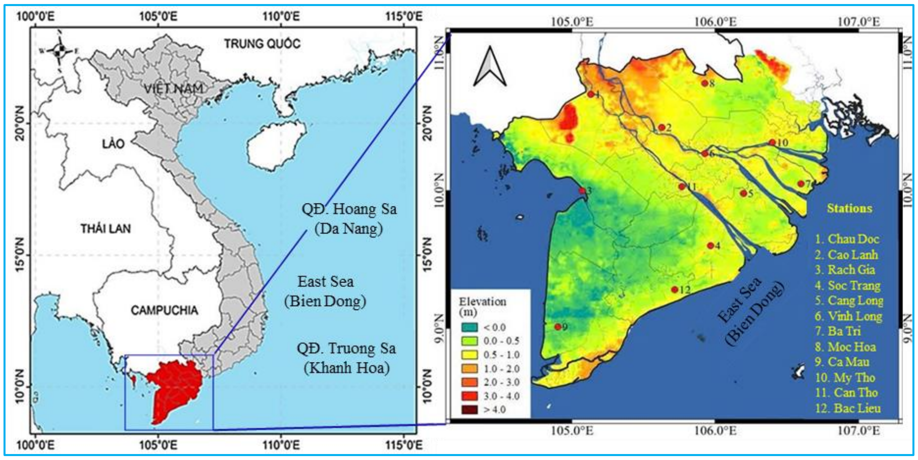


Fig. 1. Map of the study area with gauge stations marked red circle

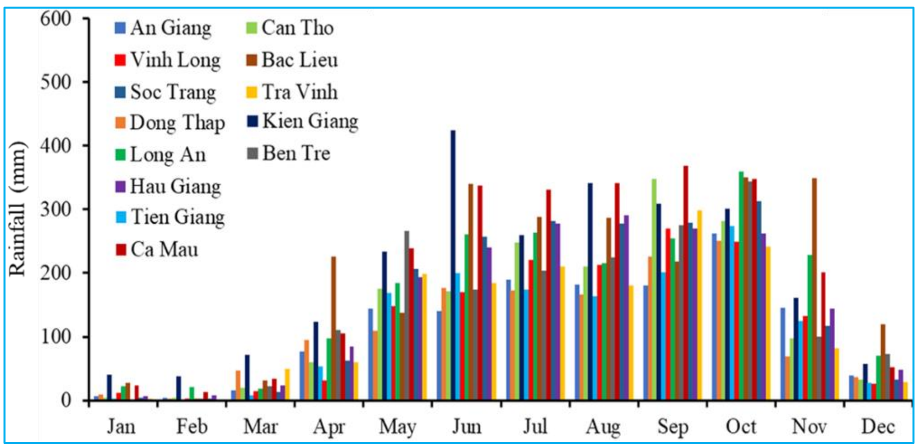


Fig. 2. Average monthly rainfall distribution in the long-term at provinces across the Vietnamese Mekong Delta

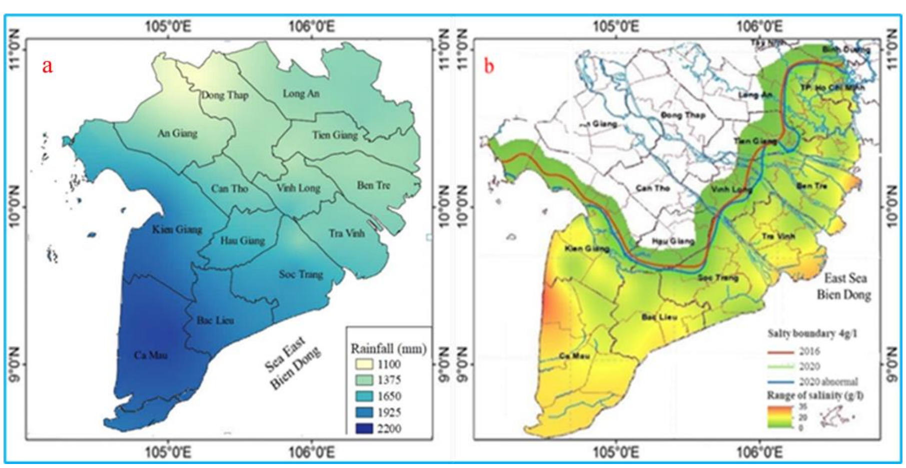


Fig. 3. Distribution of a) rainy season rainfall and b) saltwater intrusion across the Vietnamese Mekong Delta (Source: Central, Central Highlands and Southern Region Hydrological Fore-cast Office)

TABLE 1

Rainfall features in the entire Vietnamese Mekong Delta during 1982-2022

No.	Location	Latitute (N)	Longtitute (E)	Altitude (m)	Average (mm)	SD	CV	Duration
1	An Giang	10°41'24"	105°07'48"	1.2	1314	267.6	0.72	1986-2022
2	Dong Thap	10°28'05"	105°37'54"	1.3	1483	248.2	0.82	1986-2022
3	Kien Giang	10°00'00"	105°04'12"	0.3	2179	325.6	0.78	1986-2022
4	Soc Trang	09°35'60"	105°58'12"	0.8	1839	286.4	0.89	1986-2022
5	Tra Vinh	9°58'48"	106°12'00"	0.7	1646	212.9	0.89	1986-2022
6	Vinh Long	10°15'09"	105°57'53"	1.1	1436	179.1	0.88	1986-2022
7	Ben Tre	10°03'00"	106°35'60"	1.0	1485	246.8	1.03	1986-2022
8	Long An	10°46'48"	105°55'48"	1.2	1586	313.5	0.89	1986-2022
9	Ca Mau	09°10'48"	105°09'00"	0.4	2387	283.3	0.79	1986-2022
10	Tien Giang	10°21'11"	106°23'51"	1.2	1475	213.8	0.89	1986-2022
11	Can Tho	10°01'48"	105°46'12"	1.0	1602	208.9	0.94	1986-2022
12	Bac Lieu	09°16'48"	105°43'12"	0.9	1894	279.9	0.89	1986-2022

mid-May, reaching its peak in October, with more than 90% of the annual total precipitation occurring during this period (Fig. 2).

The Southwest monsoon, prevailing from May to October, brings copious rainfall amounting to 90% of the total annual precipitation, influencing the hydrological patterns of the delta (Fig. 3A). Conversely, during the dry season from November to April, the northeast monsoon brings reduced rainfall, indirectly impacting agricultural irrigation practices (Nguyen *et al.*, 2022). Coastal cultivation paddies, in particular, often confront challenges with saltwater intrusion during the dry season (Fig. 3B).

2.2. *Data collection and quality verification procedures*

Rainfall data from observation stations throughout the VMD (Fig. 1) were gathered between 1986 and 2022 from the National Center for Hydrometeorological Forecasting. The dataset underwent thorough scrutiny to assess data homogeneity, guaranteeing uniformity and applibility throughout the entire period (Table 1).

2.3. *Approach methods*

2.3.1. *Determining date of onset, length and cessation of rainy season*

The determination of the RSOD, RSCD and the LRS has been conducted based on the accumulated rainfall of five consecutive days which applied by Pham-Thanh *et al.* (2021). According to Pham-Thanh *et al.* (2021), the RSOD is defined as the day on which the 5-day moving average of the rainfall index exceeds 5 mm per day and maintains this threshold for a continuous period of at least 5 days. Furthermore, within the subsequent 20-day window, the number of days with rainfall greater than 5 mm must exceed 10-days. This method has been widely applied to determine the onset of the rainy season in Vietnam by Pham-Thanh *et al.* (2021), Bui and Dang (2024) and Ngo and Le (2025).

2.3.2. *Trend analysis of meteorology drought*

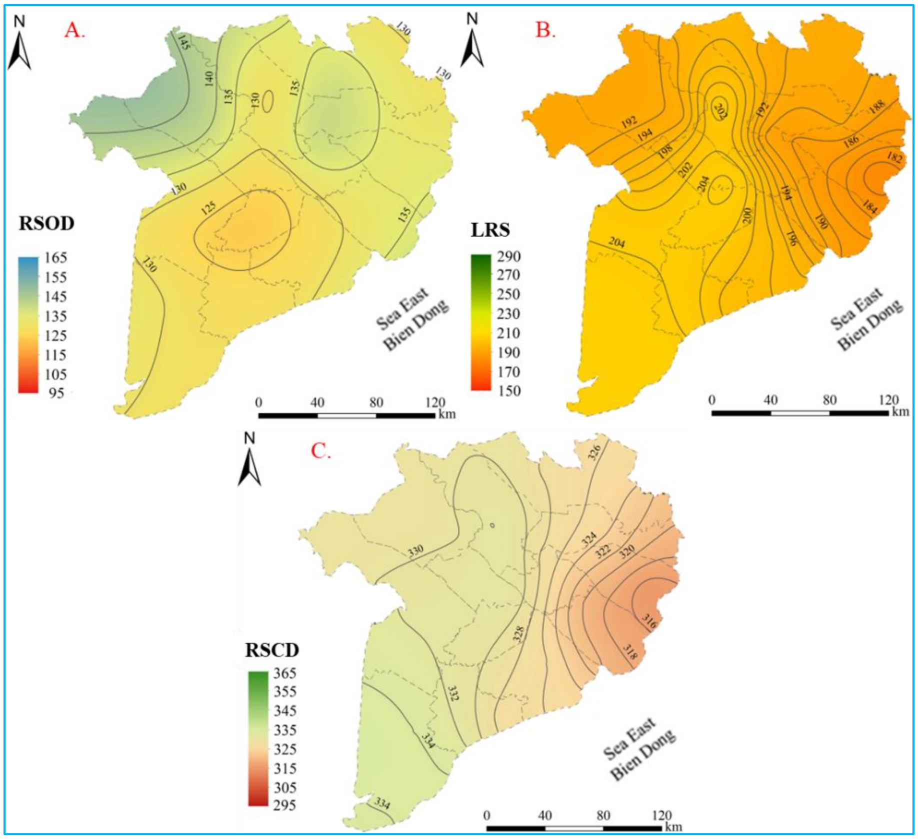
The Mann-Kendall test is used to define the change trend in the meteorology drought (Lee and Dang, 2019). The Mann-Kendall test can be defined by Eqn. (1).

$$Z_s = \begin{cases} \dfrac{S-1}{\sqrt{\mathrm{Var}(S)}} & \text{if} \quad S>0 \\ 0 & \text{if} \quad S=0 \\ \dfrac{S-1}{\sqrt{\mathrm{Var}(S)}} & \text{if} \quad S<0 \end{cases} \tag{1}$$

where S in Eqn. (1) is defined by Eqn. (2)

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \mathrm{sgn}\left(D_j - D_i\right) \tag{2}$$

With variance var (S) is defined by Eqn. (3).

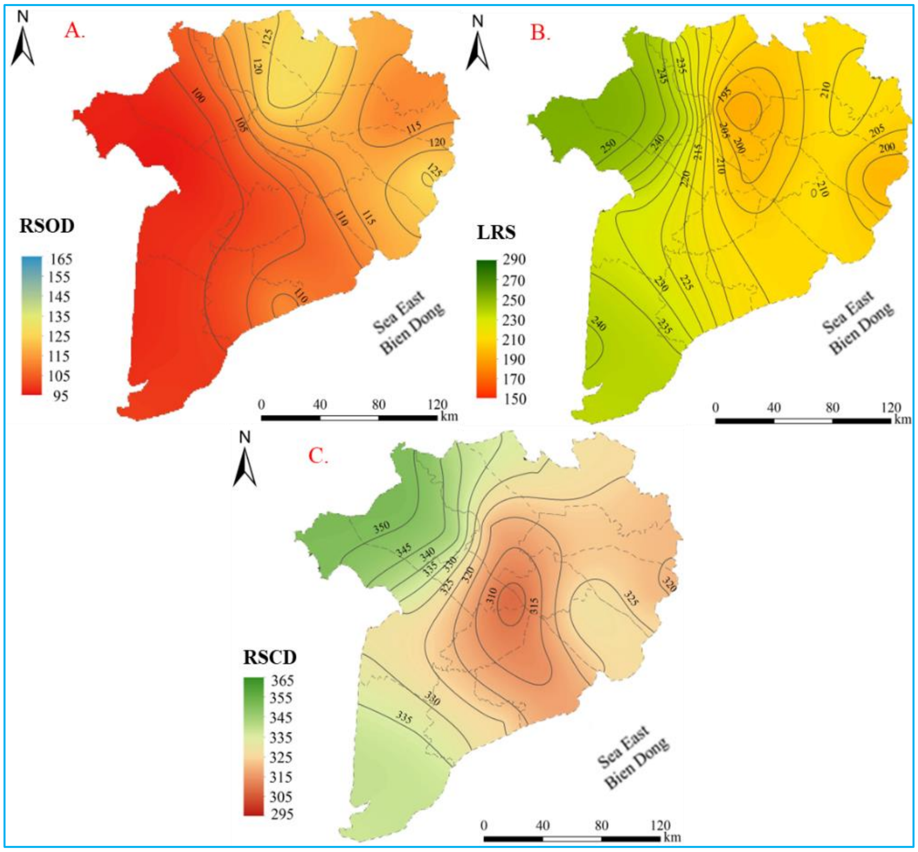


Figs. 4(a-c). The maps of (a) the rainy season onset dates, (b) the length of rainy season and (c) the rainy season cessation date across the Vietnamese Mekong Delta throughout 1986-2022

TABLE 2

Results analysis of rainfall features trends across the study area

No.	Location	Long term average (1986-2022)			La-Nina event (1999-2001)			El-Nino event (2014-2016)		
		RSOD	LRS	RSCD	RSOD	LRS	RSCD	RSOD	LRS	RSCD
1	An Giang	136	194	330	106	235	341	154	196	350
2	Dong Thap	130	202	332	124	197	321	148	186	334
3	Kien Giang	133	195	328	117	203	320	145	175	320
4	Soc Trang	128	198	326	106	208	314	134	204	338
5	Tra Vinh	133	187	320	117	211	328	142	172	314
6	Vinh Long	138	190	328	117	199	316	145	190	335
7	Ben Tre	134	181	315	125	196	321	137	169	306
8	Long An	135	193	328	128	202	330	154	192	346
9	Ca Mau	129	205	334	99	237	336	140	208	348
10	Tien Giang	134	189	323	111	211	322	152	171	323
11	Can Tho	128	203	331	107	201	308	134	204	338
12	Bac Lieu	128	199	327	111	214	325	132	198	330
	Average	132.2	194.7	326.8	114.0	209.5	323.5	143.1	188.8	331.8



Figs. 5(a-c). The maps of (a) the rainy season onset dates, (b) the length of rainy season and (c) the rainy season cessation date across the Vietnamese Mekong Delta in the typical La-Nina event of 1999-2001

$$\mathrm{var}(S) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{j=1}^{m} t_j(t_j-1)(2t_j+5)\right] \quad (3)$$

when sgn (D_j – D_i) in Eqn. (2) is calculated by Eqn. (4) :

$$\mathrm{sgn}(D_j - D_i) = \begin{cases} +1 & \text{if} \quad D_j - D_i > 0 \\ 0 & \text{if} \quad D_j - D_i = 0 \\ -1 & \text{if} \quad D_j - D_i < 0 \end{cases} \quad (4)$$

where D_j and D_i are the annual data series; j and i have the condition of $j > i$.

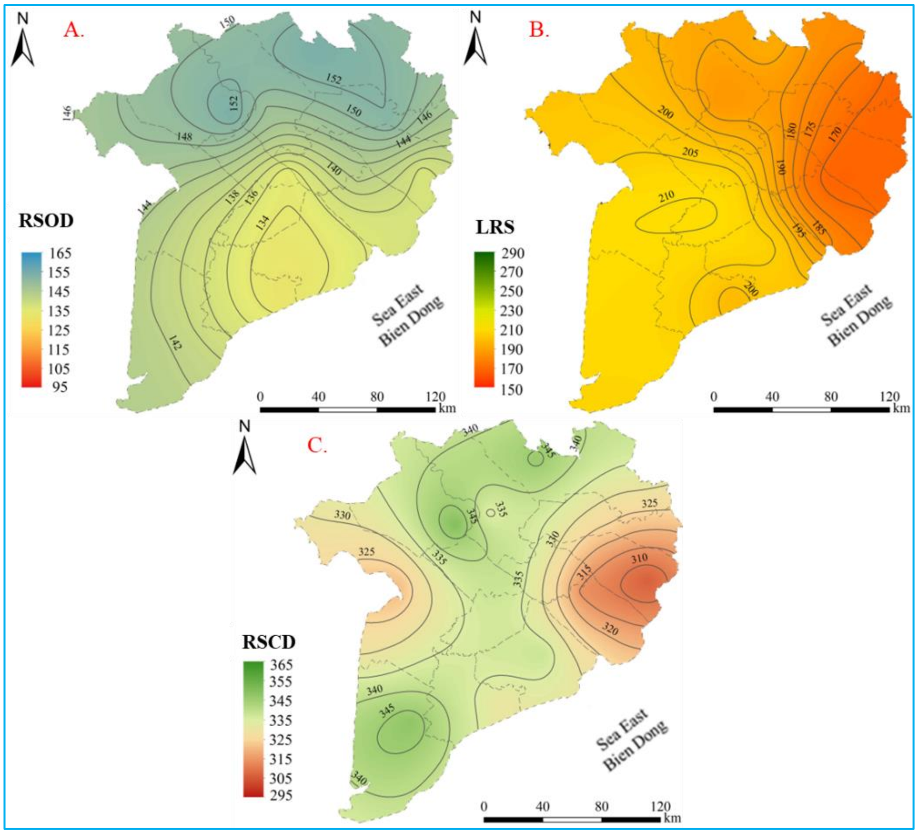
In Eqn. (4), the sign (D_j – D_i) is a function symbol. For a given α, if $|Z| \geq Z_{1-\alpha/2}$, there is a significant trend in the date of onset of wet season. In this paper, the confidence level α is taken as 0.05, and the corresponding |Z| is 1.96.

3. Results and discussion

3.1. *Relationship between ENSO events with rainfall features*

The analysis results of rainfall features across the VMD from 1986 to 2022 are presented in Table 2. The average annual rainfall in the study area is approximately 1812 mm, exhibiting high variability with a standard deviation ranging from 179.1 to 325.6 and a coefficient of variation (CV) ranging from 0.72 to 1.03.

The findings regarding the RSOD, LRS, and RSCD for the long-term average (1986-2022), typical La-Nina event (1999-2001) and El-Nino event (2014-2016) are outlined in Figs. 4-6. The average RSOD across the VMD was observed on the 132.2nd day, with provinces such as Can Tho, Soc Trang, Bac Lieu, and Ca Mau experiencing an early RSOD (128th day) during 1986-2022 (Fig. 4A). In contrast, the northern provinces like An Giang, Long An, and Vinh Long recorded RSOD later than other regions



Figs. 6(a-c). The maps of (a) the rainy season onset dates, (b) the length of rainy season and (c) the rainy season cessation date across the Vietnamese Mekong Delta in the typical El-Nino event of 2014-2016

(ranging from the 134th to 138th day). The average RSCD for the entire VMD was on the 326.8th day (Fig. 4C), with the LRS approximately 194.7 days (Fig. 4B). Ben Tre province exhibited the earliest RSCD (315th day) and the shortest LRS (181 days) compared to other provinces. Provinces like An Giang, Dong Thap, Can Tho, and Ca Mau showed the latest RSCD (ranging from the 330th to 334th day) (Fig. 4C), with an average LRS of approximately 201 days. A study on rainfall changes under the influence of climate change by Pham and Phan (2022) highlighted that RSOD demonstrated a high level among observation stations.During the typical La-Nina event in 1999-2001, the average RSOD across the VMD occurred on the 114th day, with early RSOD (around the 106th days) in provinces like An Giang, Can Tho, Soc Trang, and as early as the 99th day in Ca Mau province (Fig. 5A). Meanwhile, provinces like Long An, Dong Thap, and Ben Tre experienced a later RSOD compared to other provinces in the VMD, ranging from the 124th to 128th day (Fig. 5B).

The average RSCD for the entire VMD was on the 323.5th day during this stage (Fig. 5C).In particular, Vinh Long and Soc Trang provinces had early RSCD (around the 314th day), with rainfall during the rainy season reaching 1772 and 2330 mm and the LRS lasting 199 and 208 days, respectively (Fig. 5B). Overall, there was no significant difference in RSOD during the typical La-Nina event (1999-2001) compared to the long-term average (1986-2022), but the LRS was 4.8 days longer than the VMD average (Fig. 5). In the extreme El-Nino event from 2014-2016, the average RSOD across the VMD was on the 143.1st day, with early RSOD (around the 132nd) in provinces like Bac Lieu, Soc Trang, and Can Tho, while provinces like Long An, Tien Giang, and An Giang had a later RSOD compared to others, ranging from the 152nd to 154th day (Fig. 6A).

The average RSCD for the entire VMD was on the 331.8th day. Notably, Kien Giang, Tra Vinh and Ben Tre provinces had an early RSCD, with Ben Tre province ending the rainy season early on the 306th day, lasting 169 days with observed rainfall of only 1311 mm (Fig. 6C). In the typical El-Nino (2014-2016), there was an approximate 10.9-day delay in RSOD compared to the long-term average, a 5.0-day delay in RSCD, and the LRS

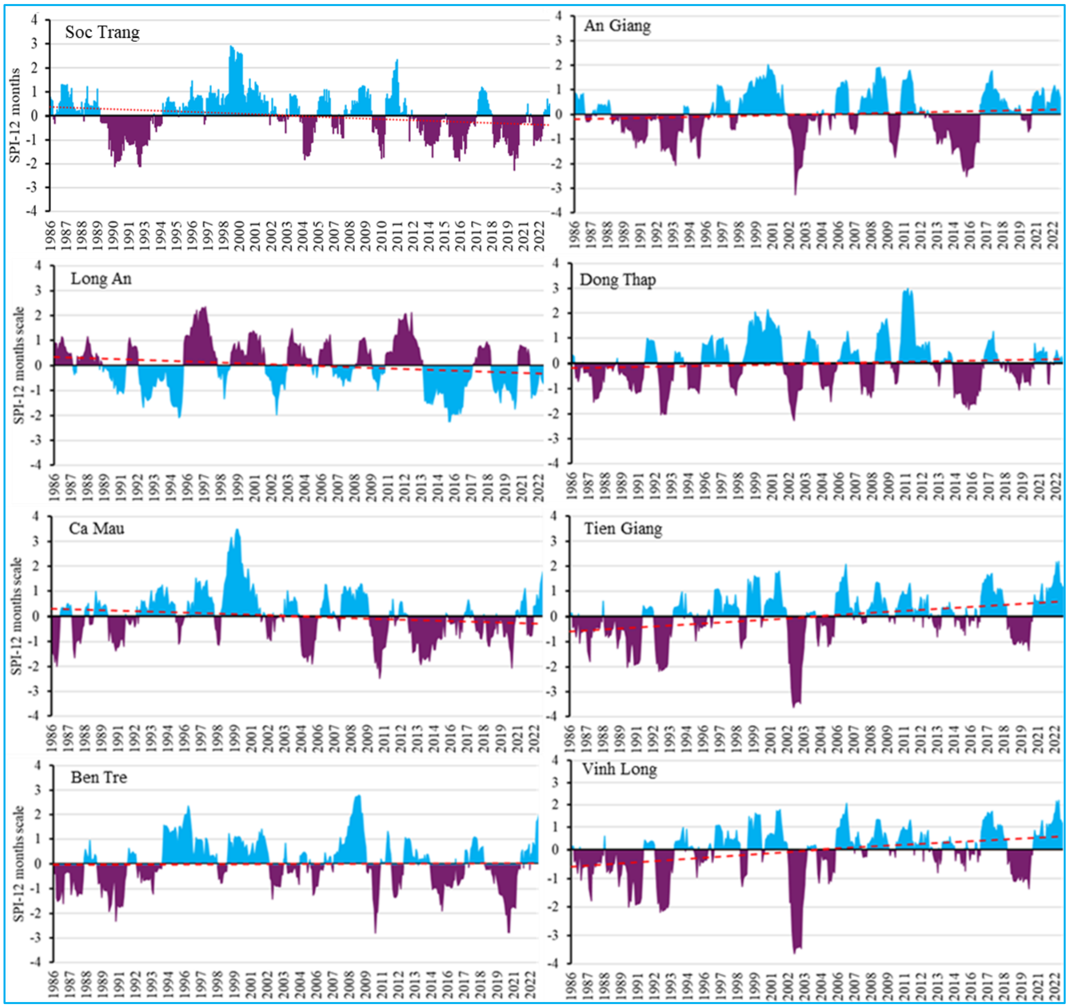


Fig. 7. Typical La-Nina and El-Nino phases occurred in the Vietnamese Mekong Delta during the period 1986-2022

TABLE 3

Results of SPI12 calculated across the Vietnamese Mekong Delta during the period 1986-2022

Location	Long term average (1986-2022)		La-Nina event (1999-2001)			El-Nino event (2014-2016)		
	$SPI12_{min}$	$SPI12_{max}$	1999	2000	2001	2014	2015	2016
An Giang	-3.26	2.03	1.37	2.03	1.77	-1.68	-3.05	-1.16
Dong Thap	-2.30	3.00	2.05	2.15	1.69	-1.22	-1.84	-1.62
Soc Trang	-2.26	2.93	1.62	1.56	1.74	-1.71	-1.73	-1.87
Vinh Long	-3.63	2.20	1.61	1.58	1.79	-0.38	-0.73	-0.42
Ben Tre	-2.81	2.80	1.11	1.09	1.42	-1.03	-1.91	-0.97
Long An	-2.25	2.36	0.96	1.38	1.35	-1.49	-2.81	-2.07
Ca Mau	-2.47	3.49	3.49	3.49	1.12	-1.79	-0.91	-0.86
Tien Giang	-3.63	2.20	1.05	2.67	0.98	-1.76	-2.03	-0.38

was 5.9 days shorter (Fig. 6B). The analysis results of weather variations across the VMD, as indicated by the SPI12 calculated with a 12-month timescale from 1986 to 2022, is presented in Table 3. The results reveal that during the typical La-Nina event of 1999-2001, the weather progression in the VMD region, as assessed by the SPI12 index, ranged from 1.74 to 3.19. The results suggest a shift in weather conditions in the VMD from moderately to extremely wet during the period of 1999-2001. Examining the weather patterns in the study area during the typical El-Nino event in 2014-2016 showed that the VMD encountered weather conditions varying from near normal to extremely dry, with SPI12 values fluctuating from -0.89 to -2.52 (Fig. 7).

Analyzing the weather trends in the VMD from 1986 to 2022 using the Mann-Kendall test, as illustrated in Fig. 7, revealed that coastal provinces like Ca Mau, Tra Vinh, Bac Lieu, Ben Tre, Kien Giang, Soc Trang and Long An experienced a slight increase in drought trends. In contrast, provinces such as Vinh Long, An Giang and Tien Giang observed a slight decrease in drought trends. Overall, the analysis of weather developments in the VMD region during the 1986-2022 period indicates that most coastal provinces in the VMD are at an elevated risk of diminishing rainfall, resulting in adverse impacts on agricultural productivity and heightened salinity intrusion.

3.2. *Research limitations*

The scope of our analysis was concentrated to several representative stations across the study area. While the VMD is a wider geographical range to enhance the generalizability of our findings. Our study only focused on the influence of ENSO phenomanon on rainfall features. Other factors can dominate rainfall features but not mentioned in this study.

4. Conclusions

This study investigated the influence of ENSO phenomena and rainfall features across the Vietnamese Mekong Delta using daily rainfall data from 1986 to 2022. Findings reveal that La-Nina and El-Nino events significantly dominated the rainfall features across the study area, with typical La-Niña event in the stage 1999-2001 was driven by the early appearance of the RSOD while El-Niño event leading to a delayed onset of the rainy season during the stage 2014-2016. This study underscores the vulnerability of Vietnamese Mekong Delta rice cultivation to ENSO-driven climate variability and emphasizes the need for proactive adaptation strategies to mitigate the impacts of climate variability on food security. Future research should focus on developing and implementing region-specific adaptation measures, such as drought-tolerant rice varieties and improved water management practices, to enhance the resilience of the Vietnamese Mekong Delta's rice production system.

Authors' contributions

T.V.H. Hoang: Conceptualization, validation, formal analysis, writing-original draft preparation, writing-review and editing

T.A. Dang: Conceptualization, methodology, formal analysis, writing-original draft preparation, writing-review and editing

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