atmosphere

MDPI

Article

Spatiotemporal Variations and Characteristics of the El Niño–Southern Oscillation (ENSO) Phenomenon from 1950 to 2023

Pei-Hua Wu [1,2], Chun-Han Lin [3], Haonan Chen [4], Liangwei Wang [4] and Chung-Ru Ho [1,*]

[1] Department of Marine Environmental Informatics, National Taiwan Ocean University, Keelung 202301, Taiwan; 21181001@mail.ntou.edu.tw
[2] National Museum of Marine Science and Technology, Keelung 202010, Taiwan
[3] Department of Computer Science and Engineering, National Taiwan Ocean University, Keelung 202301, Taiwan; 10957004@mail.ntou.edu.tw
[4] Electrical and Computer Engineering, Colorado State University, Fort Collins, CO 80523, USA; haonan.chen@colostate.edu (H.C.); liangwei.wang@colostate.edu (L.W.)
* Correspondence: b0211@mail.ntou.edu.tw

Abstract

The El Niño–Southern Oscillation (ENSO) is one of the most important climate phenomena on Earth due to its impacts on the global atmospheric circulation. This paper conducts a comprehensive analysis of the spatiotemporal variations and characteristics of ENSO from 1950 to 2023. A number of indices, including the Oceanic Niño index, Modoki index, and the modified El Niño Modoki Index, were used to differentiate between various ENSO types and assess their respective impacts on the global climate. The analysis reveals notable changes in the frequency and intensity of ENSO events over the past seven decades. Notably, since 1990, the sea surface temperature anomalies (SSTAs) in the tropical Western Pacific regions have shifted westward by approximately 18 degrees longitude, potentially a result of global warming. During the same time period, the frequency and intensity of ENSO events have also changed, with an increase in the frequency of Central Pacific El Niño events and a decline in the frequency of Eastern Pacific El Niño events. The occurrence frequency of both Central and Eastern Pacific La Niña events has remained relatively stable but shows some variability. Based on the analysis results, this article also suggests potential improvement in data collection, which is critical to further understanding and verification of the spatiotemporal variations of ENSO events.

Keywords: El Niño–Southern Oscillation (ENSO); sea surface temperature anomalies (SSTA); Oceanic Niño index (ONI); Modoki index

check for updates

Academic Editors: Netrananda Sahu and Sridhara Nayak

Received: 21 July 2025
Revised: 22 October 2025
Accepted: 2 November 2025
Published: 5 November 2025

Citation: Wu, P.-H.; Lin, C.-H.; Chen, H.; Wang, L.; Ho, C.-R. Spatiotemporal Variations and Characteristics of the El Niño–Southern Oscillation (ENSO) Phenomenon from 1950 to 2023. *Atmosphere* **2025**, *16*, 1264. https://doi.org/10.3390/atmos16111264

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

The Earth's climate is a complex and dynamic system influenced by various factors. Among these, the El Niño–Southern Oscillation (ENSO) is one of the most significant variations within the global climate system, having far-reaching impacts on the climate and ecosystems worldwide [1–10]. In recent years, with the intensification of climate warming, scientific interest in ENSO has grown considerably. The ENSO phenomenon refers to the coupled interaction between the ocean and the atmosphere in the tropical Pacific region, initiated primarily by the periodic occurrence of El Niño and La Niña events. The ENSO cycle typically spans from 2 to 7 years and leads to significant climate anomalies worldwide. El Niño events are generally associated with warming in the eastern Pacific Ocean and

widespread climatic anomalies, whereas La Niña events are characterized by cooling in the eastern Pacific.

Recent advances have revealed that ENSO is far more complex than the conventional view of a simple oscillation between warm and cold phases. Timmermann et al. [1] demonstrated that ENSO is a highly nonlinear, multi-modal coupled system whose complexity intensifies under background-state changes. This evolving complexity underscores the need to re-evaluate how ENSO is monitored and classified under a warming climate, given that its influence extends far beyond the tropical Pacific through global atmospheric and oceanic teleconnections.

As global climate change intensifies, studying the ENSO phenomenon has become increasingly important. Climate warming may alter the frequency, intensity, and spatiotemporal distribution of ENSO events, consequently impacting global climate patterns and ecosystems. Therefore, an in-depth study of the ENSO phenomenon and its effects on global climate is essential to understand and respond to climate change.

Over the past few decades, numerous studies have been conducted on this topic. Chen et al. [11] analyzed the spatial and temporal distribution of ENSO events, revealing significant changes in their occurrence and duration across different periods and regions. Yang et al. [8] used climate models to simulate future climate change scenarios, highlighting noticeable trends of increasing frequency and intensity for both El Niño and La Niña events. It is suggested that climate change may alter the frequency and intensity of ENSO events. Building upon this foundation, Ashok et al. proposed the El Niño Modoki Index (EMI) to distinguish central-Pacific–type events [12], in which the maximum sea surface temperature anomaly (SSTA) occurs near the dateline and produces teleconnections distinct from canonical eastern-Pacific events.

However, significant uncertainties and debates remain regarding the relationship between the spatiotemporal evolution of ENSO events and climate change. In particular, the feedback effects of ENSO on regional climates, along with its overall influence on global climate change is not yet fully understood. Therefore, this study seeks further exploration on the spatiotemporal relationship between ENSO events and climate change, building upon previous research to provide more robust evidence and informed recommendations.

Kao and Yu [13] further demonstrated that eastern-Pacific (EP) and central-Pacific (CP) El Niño events differ in intensity, lifecycle, and atmosphere–ocean coupling, underscoring that a single index cannot fully describe ENSO diversity.

To accurately observe and analyze ENSO events, scientists have proposed various observation and analysis methods [14]. Among these, the Pacific Ocean temperature indices, such as the Oceanic Niño Index (ONI) index and Modoki index, are widely used to monitor the occurrence and development of ENSO events [12]. Larkin and Harrison [15] systematically defined ONI thresholds and their seasonal climate relationships, verifying ONI as a robust metric for detecting ENSO phases. The ONI is based on the SSTAs in the equatorial central Pacific and is used to identify El Niño and La Niña events by defining SSTAs. The Modoki index further refines the traditional classification for El Niño events, describing an El Niño Modoki event when SSTAs are concentrated in the central Pacific, while temperatures in the eastern and western Pacific remain relatively normal. The Modoki index is an important indicator for understanding various types of ENSO events and their impacts on global climate.

According to the National Oceanic and Atmospheric Administration (NOAA) and related studies [16], the ONI is one of the key indicators for measuring the ENSO phenomenon. The ONI is calculated as a three-month moving average of SSTAs in the central-eastern tropical Pacific region (Niño 3.4 area). It has been widely adopted for tracking and predicting ENSO evolution and for investigating the associated physical mechanisms and

global climatic impacts. When the ONI value exceeds ±0.5 °C for at least five consecutive overlapping seasons, the corresponding period is defined as an El Niño or La Niña event, respectively.

The Modoki Index (El Niño Modoki Index, EMI), proposed by Ashok et al. [12], is used to describe a climate phenomenon different from the traditional El Niño, known as La Niña. This phenomenon is characterized by abnormal sea surface temperatures in the central Pacific, while temperatures in the eastern and western Pacific remain relatively normal. The El Niño Modoki phenomenon can lead to different patterns of climate impact, such as abnormal winter climates, and the Modoki index has potential in analyzing the spatial distribution changes of the Southern Oscillation.

This study aims to thoroughly investigate the spatiotemporal variations and characteristics of ENSO events from 1950 to 2023 and explore their effects on global climate. Through observational data and statistical methods, we hope to reveal the patterns of change in ENSO events, examine their relationship with global climate change, and provide scientific evidence for future climate predictions and climate change response strategies. Based on the relevant studies such as Ashok et al. [12] and Trenberth and Stepaniak [14], this research intends to examine in-depth the temporal and spatial changes of the El Niño–Southern Oscillation phenomenon before and after 1990 and analyze its impacts on global climate. Through these analyses, our aim is to provide valuable references for understanding the long-term trends of the ENSO phenomenon and future climate predictions. In particular, it will focus on ONI and EMI, which will provide essential insights into the temporal evolution and geographic distribution of different ENSO types.

2. Datasets and Analysis Methods

This study aims to analyze the spatiotemporal evolution of the ENSO phenomenon through historical data, exploring its trends and patterns from 1950 to 2023. As a major driver of global climate variability, ENSO has far-reaching impacts on weather systems, so establishing a comprehensive understanding of its spatiotemporal dynamics is essential.

To analyze the spatiotemporal variations of the ENSO phenomenon, this study collected and organized ENSO-related data from 1950 to 2023. We used NOAA's sea surface temperature anomaly data (ERSSTv5) to calculate the ONI and EMI indices and conducted an in-depth study using statistical analysis methods. The ONI index is based on SSTAs in the Niño 3.4 region (5° N–5° S, 120° W–170° W), while the EMI index is calculated using SSTAs in the central Pacific (165° E–140° W, 10° S–10° N), eastern Pacific (110° W–70° W, 15° S–5° N), and western Pacific (125° E–145° E, 10° S–20° N).

However, it should be noted that the reliability of SST-based indices is not uniform across the entire study period. In earlier decades, particularly before the widespread deployment of satellites and buoys in the 1980s, sea surface temperature observations were relatively sparse and relied mainly on ship-based measurements. As a result, the reconstructed datasets for those periods may contain higher levels of uncertainty compared with more recent decades [17–19]. This limitation is inherent to long-term climate reconstructions and should be considered when interpreting ENSO variability over the full 1950–2023 period.

In this article, ONI is calculated based on the SSTA values in the Niño 3.4 region, using a three-month running average. EMI proposed by Ashok et al. [12], calculates the difference between SST anomalies in the central Pacific ($SSTA_c$) and the average of SST anomalies in the eastern ($SSTA_e$) and western Pacific ($SSTA_w$):

$$EMI = SSTA_c - 0.5SSTA_e - 0.5SSTA_w. \quad (1)$$

Similar to Li et al. [20], we use 1990 as the dividing point in this study since significant shifts in the spatial pattern and temporal evolution of ENSO were discovered near 1990, including where ENSO events occur and how long they last. The traditional EMI tends to underestimate events dominated by east–west thermal gradients, especially under the increased complexity of post-1990 ENSO behavior. In order to better capture the spatial asymmetry between Central Pacific (CP) and Eastern Pacific (EP) events, this study introduces a modified El Niño Modoki Index (EMI-e), expressed as:

$$\text{EMI-e} = \text{SSTA}_c - \text{SSTA}_e. \quad (2)$$

This simplified formulation removes the western-Pacific term to exclude the influence of the warm-pool region (125° E–145° E), which often introduces background variability unrelated to ENSO core dynamics. The EMI-e emphasizes the zonal SST contrast between the central and eastern Pacific, thereby enhancing its sensitivity to the east–west thermal gradient within the ENSO core region. Physically, this design allows EMI-e to better represent the relative strength and contrast of SST anomalies.

The newly introduced EMI-e index is used to investigate the development trends of El Niño and La Niña events. By analyzing the changes in the ONI, EMI, and EMI-e indices before and after 1990, the study aims to understand the dynamic characteristics and spatial distribution patterns of the ENSO phenomenon during this period, revealing its impact on the global climate system.

Based on processed SSTA data and ENSO index data, this study conducted various statistical analyses. Firstly, it analyzed the spatiotemporal changes in SSTAs, including the average values, trend changes, and spatial distribution of SSTA over different periods. Secondly, using ENSO index data, the study examined the occurrence frequency, intensity, and types of ENSO events, including cross-annual temperature changes, temporal changes, spatial changes, and distinctions between El Niño and La Niña events and Central Pacific and Eastern Pacific events.

To ensure methodological clarity and reproducibility, the analytical process was conducted in a step-by-step manner: (1) Monthly SSTAs were calculated relative to the 1981–2010 climatology and detrended at each grid point. (2) The ONI was computed as the 3-month running mean of SSTAs averaged over the Niño 3.4 region (5° N–5° S, 170°–120° W). (3) The EMI and EMI-e indices were derived following step (1)–(2). (4) El Niño (La Niña) events were identified when ONI $\leq +0.5$ °C (≤ -0.5 °C) for at least five consecutive overlapping seasons. (5) Events were further classified as EP-type or CP-type according to the sign of the EMI-e during their peak phase. (6) For each event, intensity, duration, and temporal evolution were analyzed, and composite SSTAs maps were constructed to examine spatial patterns and regime shifts before and after 1990.

3. Results and Discussion

This section presents the observed spatiotemporal changes in SSTA from 1950 to 2023, highlighting their correlation with ENSO events. The analysis compares the trend changes in SSTA during two distinct periods: 1950–1990 and 1991–2023.

3.1. Spatiotemporal Changes in Sea Surface Temperature Anomalies

Between 1950 and 1995 a generally negative trend in SSTA was observed, indicating that sea temperatures were consistently lower than normal, which aligns with findings from previous studies (e.g., [14]). Although isolated warming events occurred during this period, the overarching trend was cooler oceanic conditions in the tropical Pacific. These cooler temperatures reflect a period when ENSO events were not as frequent or intense like those in later years. Similarly, the oceanic and atmospheric conditions in this region

remained relatively stable as well. The westward trend corresponds to the findings of Yeh et al. [21], who reported that CP-type El Niño events have become more frequent under global warming, indicating a modification of the background Pacific state.

From 1991 to 2023, a positive SSTA became evident, indicating an overall increase in sea temperatures. This trend corresponds with the broader global warming phenomenon where sea temperatures in the tropical Pacific began to rise significantly. Particularly since the mid-2000s, the positive trend in SSTA has intensified, likely due to factors such as the accumulation of heat in tropical oceans and shifts in ocean circulation patterns driven by global climate change [22]. The more pronounced warming during this period suggests a growing influence of global warming on the tropical Pacific region, affecting ENSO events and their global impacts.

In Figure 1, the period from 1950 to 1990 shows a negative trend in sea surface temperatures, indicating below-normal levels, which is consistent with other research findings. Despite some warming events during this period, the overall sea temperatures remained relatively low, suggesting a cooler environment in the tropical Pacific. In contrast, during the period from 1991 to 2023, SSTAs exhibited a positive trend, indicating above-normal levels. This aligns with the global warming trend and may be related to global warming and changes in ocean circulation.

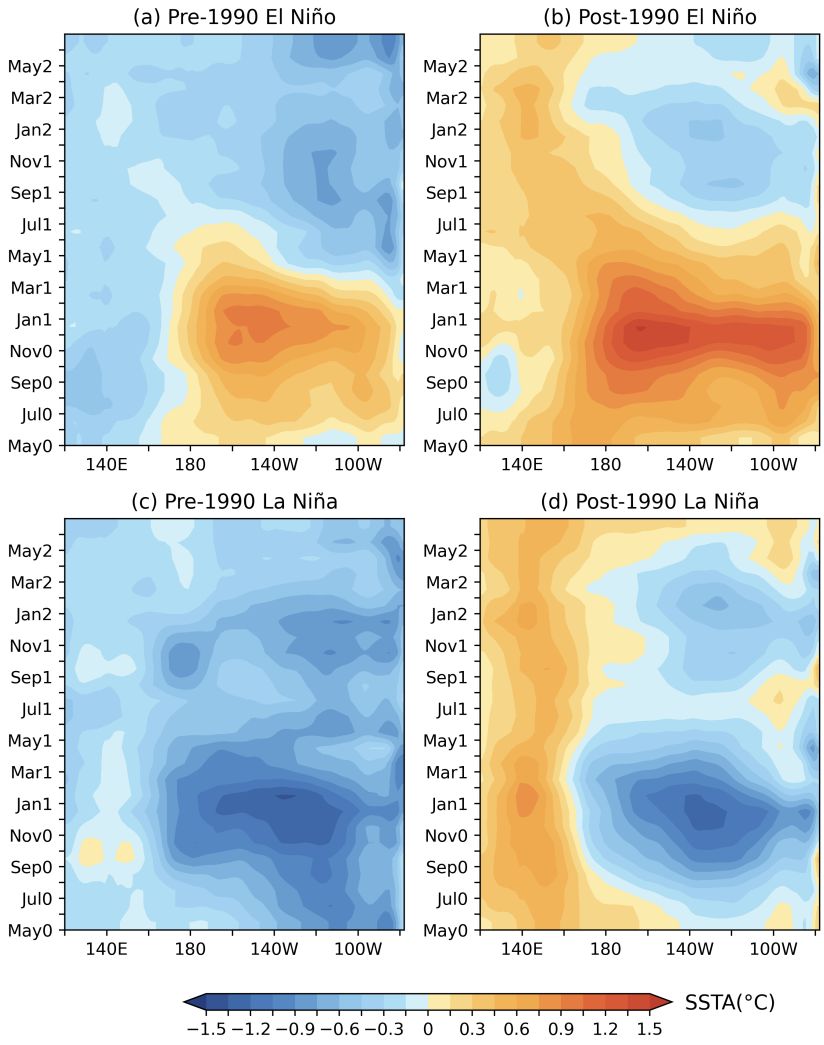


Figure 1. Hovmöller diagram of El Niño and La Niña events before and after 1990.

During El Niño events, sea temperatures in the central and eastern equatorial Pacific increase, while those in the western Pacific decrease. After 1990, the scope of El Niño events expanded, and their intensity also increased. During La Niña events, sea temperatures in the central and eastern equatorial Pacific decrease, while those in the western Pacific increase. Post-1990 La Niña events showed abnormal warmth in the western Pacific, with a longer duration.

3.2. ENSO Event Periodicity Changes

During the study period, an in-depth analysis of the periodic changes in ENSO events was conducted, mainly focusing on the ONI and EMI-e indices as the basis for determining ENSO events and exploring the trend changes and relevant characteristics of these indices from 1950 to 2023.

3.2.1. Significant Periods of ENSO Events

Significant variations in ENSO activity have been observed in recent decades, with both the frequency and intensity of events becoming increasingly pronounced. From Table 1, it can be seen that between 1950 and 2023, there were 19 El Niño and 12 La Niña events, generally recurring every 2 to 7 years. During 1950–1990, El Niño events occurred relatively infrequently, around 2 to 3 times per decade, but their occurrence increased notably from 1991 onward, reaching 4 to 5 times every 10 years. The intensity of El Niño events also strengthened after 2000, peaking in 2015–2016 with one of the most severe episodes in recorded history.

Similarly, La Niña events exhibited a marked rise in both frequency and strength after the 1980s. Between 1990 and 2023, their occurrence became more frequent and intense, especially during 2020–2022 when extended, multi-year La Niña conditions were observed. Taken together with the results from Table 1 and Figure 1, it is evident that since the 1990s, ENSO events have shown enhanced variability, with El Niño peaking in strength during the mid-2000s and La Niña episodes becoming more frequent in the 2010s, indicating a long-term amplification of ENSO activity.

Table 1. Duration and Frequency of El Niño and La Niña (ONI Index).

Periods	Type	Year of Occurrence	Duration (years)	Single Year Events	Multi-Year Events	Frequency (years/event)
1950–1990	El Niño	1951, 1953, 1957, 1965, 1969, 1972, 1976, 1982, 1986	1, 1, 1, 1, 1, 1, 1, 1, 1	9	0	4.56
	La Niña	1950, 1954, 1955, 1964, 1970, 1973, 1975, 1988	1, 2, 1, 1, 1, 1, 1	6	1	5.13
1991–2023	El Niño	1991, 1994, 1997, 2002, 2004, 2006, 2009, 2015, 2018, 2023	1, 1, 1, 1, 1, 1, 1, 1, 1, 1	10	0	3.3
	La Niña	1998, 1999, 2000, 2007, 2008, 2010, 2011, 2016, 2017, 2020, 2021, 2022	3, 2, 2, 2, 3	0	5	2.75

To assess the statistical significance of long-term changes in ENSO activity, we applied the non-parametric Mann–Kendall (M–K) test to annual ENSO occurrence series (0/1 per year) and 10-year rolling event counts, separately for 1950–1990 and 1991–2023. Table 2 shows that the annual series did not reveal significant monotonic trends in either period ($p > 0.05$), reflecting the large interannual variability and binary nature of the data. In contrast, the 10-year rolling analysis showed statistically significant upward trends after 1990, particularly for La Niña events ($Z = 6.10$, $p < 0.001$, Sen's slope = +0.125 events × year^{-1}) and total ENSO events ($Z = 4.78$, $p < 0.001$, slope = +0.118 events × year^{-1}). These findings

indicate that although ENSO variability appears relatively stable in the earlier decades, the decadal-scale frequency of events has increased substantially since the 1990s.

Table 2. Mann–Kendall test results for ENSO event frequency (1950–1990 vs. 1991–2023). (Z = standardized test statistic; p = two-sided significance; Sen's slope = Theil–Sen median slope in events × year^{-1}).

Periods	Type	Z	p	Sen's Slope	Significance
1950–1990	El Niño (annual)	−0.58	0.56	0.000	ns
	La Niña (annual)	−1.00	0.32	0.000	ns
	Total ENSO (annual)	−1.31	0.19	0.000	ns
	El Niño (10 yr rolling)	0.02	0.98	0.000	ns
	La Niña (10 yr rolling)	−1.81	0.07	0.000	ns (marginal)
	Total ENSO (10 yr rolling)	−1.39	0.17	0.000	ns
1991–2023	El Niño (annual)	−0.41	0.68	0.000	ns
	La Niña (annual)	1.67	0.10	0.000	ns (marginal)
	Total ENSO (annual)	1.28	0.20	0.000	ns
	El Niño (10 yr rolling)	−0.68	0.50	0.000	ns
	La Niña (10 yr rolling)	6.10	<0.001	0.125	***
	Total ENSO (10 yr rolling)	4.78	<0.001	0.118	***

ns = not significant; *** = significant at $p < 0.001$.

3.2.2. Changes in ONI and EMI-e Indices

The ONI index determines the occurrence of El Niño and La Niña events by monitoring SSTAs in the Niño 3.4 region. According to the research results, the ONI and EMI-e indices have exhibited significant periodic changes over the past few decades. During intense El Niño events, these indices typically show a noticeable upward trend, reflecting the abnormal rise in sea temperatures in the tropical eastern Pacific. Conversely, during La Niña events, these indices exhibit a downward trend, indicating the decline of sea temperature anomalies in that region.

From 1950 to 1979, ENSO events were less frequent and of lower intensity. From 1980 to 1999, the frequency of ENSO events increased, and from 2000 to 2023, both the intensity and frequency of ENSO events reached their peak.

As shown in Figure 2, the ONI index fluctuated less during 1950–1990, with lower intensity and frequency of El Niño and La Niña events. The ONI index mainly fluctuated within ±0.5 °C. Starting in the 1990s, the volatility of the ONI index increased significantly, particularly during the 1997–1998 and 2015–2016 El Niño events, when the ONI index reached a significant high, exceeding 2 °C. The intensity of La Niña events also increased, demonstrating a marked change in the ONI index in recent decades.

When the ONI is less than −0.5, the EMI-e usually shows positive values, indicating a below-normal condition. For example, during periods of low ONI in 1954–1955, 1994–1995, 2001, and 2013–2019, EMI-e is mostly positive.

When the ONI is greater than 0.5, the EMI-e typically shows negative values, indicating normal or above-normal conditions. For example, during high ONI periods in 1957, 1965, 1972–1976, 1982–1983, and 1997–1998, EMI-e is mostly negative.

Overall, the ONI and EMI-e indices show opposite trends: when the ONI rises, the EMI-e usually falls, and when the ONI falls, the EMI-e usually rises. This inverse relationship between ONI and EMI-e.

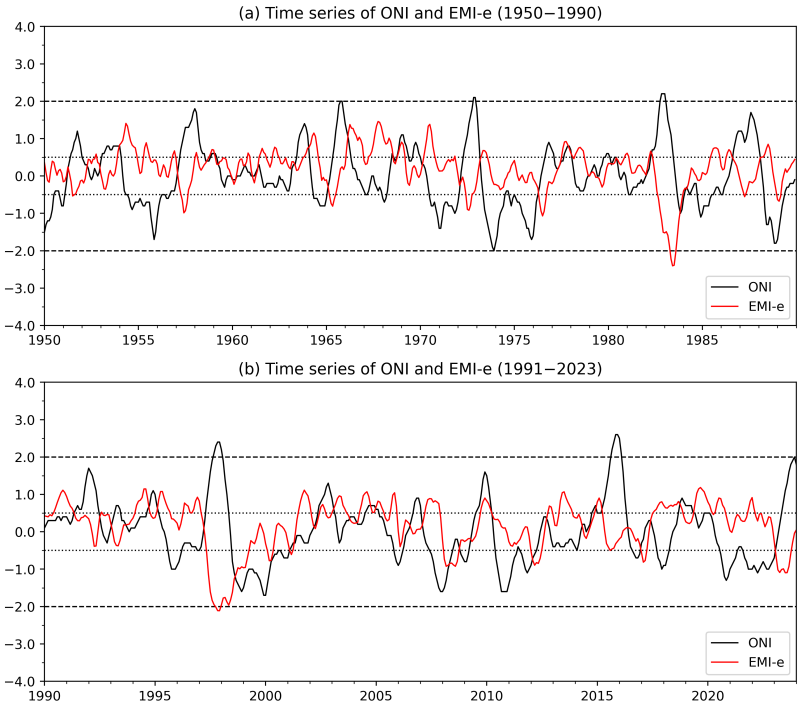


Figure 2. Comparison of the ONI (black) and the EMI-e (red) presented as line charts. Panel (**a**) corresponds to the period 1950–1990, and panel (**b**) corresponds to 1991–2023, highlighting the temporal evolution, variability, and differences between the two indices.

In some cases, the rise or fall of EMI-e precedes the change in ONI, exhibiting a leading or lagging trend. This relationship can be used for the analysis and prediction of ONI and EMI-e trends. A better understanding of this relationship could provide additional value for diagnosing ENSO dynamics, improving the characterization of different ENSO types, and potentially enhancing the performance of seasonal climate predictions. Further research and analysis would therefore be beneficial for advancing both theoretical understanding and practical forecasting applications.

3.3. Spatial Variation Trends

SSTA Distribution: Figure 3 illustrates the spatial distribution characteristics of SSTA during different ENSO events. During El Niño events, SSTAs in the central and eastern equatorial Pacific increase significantly, while the western sea temperatures decrease. In contrast, during La Niña events, SSTAs in the central and eastern equatorial Pacific decrease, while the western sea temperatures increase.

Figure 3 shows that after 1990, the average value of SSTA shifted westward by 18 degrees. From 1950 to the mid-2000s, the SSTA values in the central and eastern equatorial Pacific showed a negative trend, indicating below-normal sea temperatures. Subsequently, the SSTA values displayed a positive trend from the mid-2000s onward. Since 2010, the fluctuation range of SSTA values has increased, indicating more intense sea temperature changes. After 2000, during La Niña events, the sea surface temperature in the central Pacific was higher than normal, which may be related to the impact of global warming in recent years, suggesting that climate change in this region is intensifying.

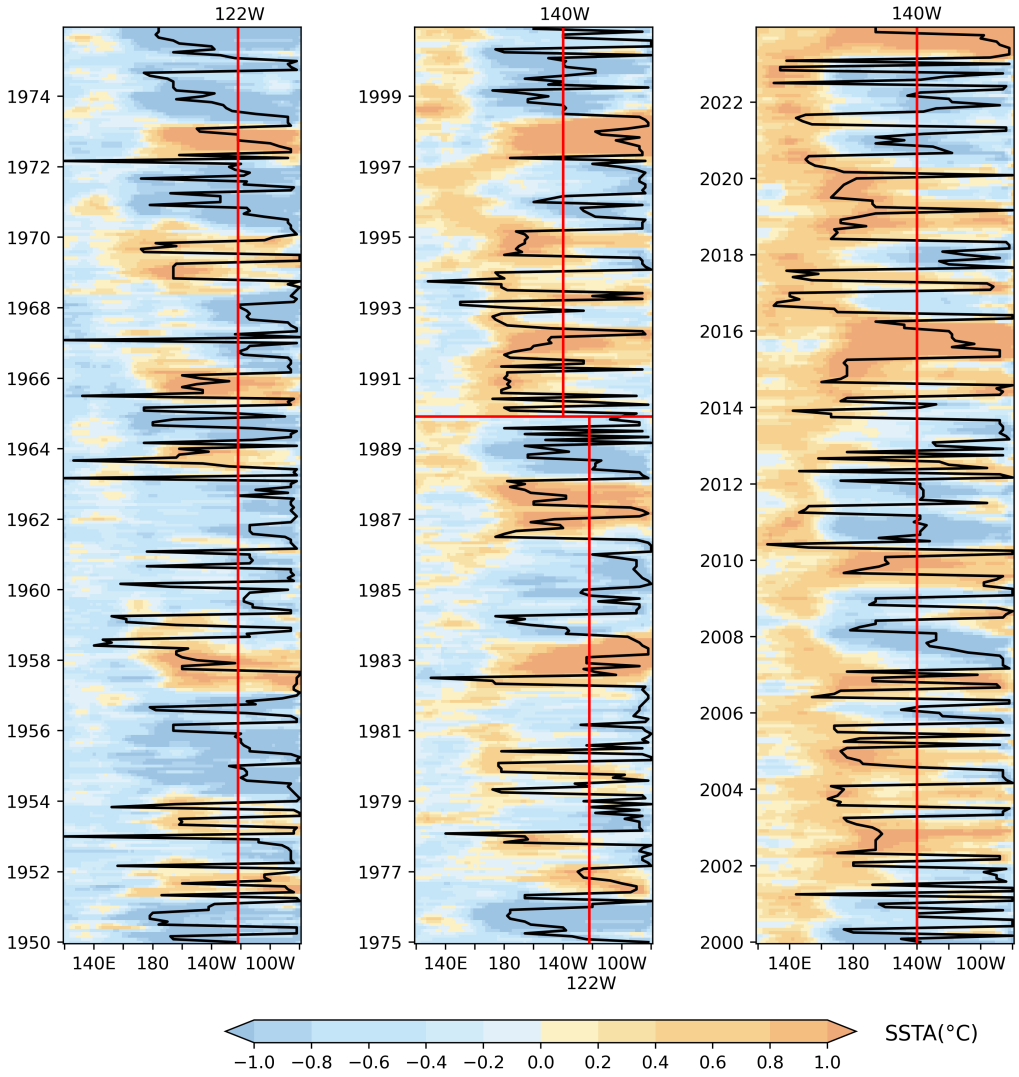


Figure 3. Hovmöller diagram showing the evolution of SSTA over the equatorial central-to-eastern Pacific. The black line indicates the location of the maximum absolute value (either peak or trough) of SSTA. The two red lines, divided at 1990, indicate the mean values for the periods 1950–1990 and 1991–2023, respectively.

Historically, ENSO events were described as Eastern Pacific (EP) events because the eastern Pacific was the most warming area. However, as shown in Table 3, over the past 40 years, the frequency of Central Pacific (CP) events has increased, with a total of 10 Modoki El Niño events occurring. The strongest Modoki El Niño event occurred in 2009–2010, with an EMI value of 1.5 °C. The frequency of Modoki El Niño has increased significantly after 1990, especially after the 2000s.

Analysis shows that there is some overlap between the ONI and EMI indices in certain years, but they do not always occur synchronously. This suggests that while both indices are associated with ENSO events, their underlying driving mechanisms and impacts differ. The warming anomaly of Modoki El Niño is more pronounced in the central Pacific, while the traditional El Niño is concentrated in the eastern Pacific.

Table 3. Types and Occurrence Frequency of El Niño and La Niña Events (EMI-e Index).

Type	Period	Year and Duration	Number of Occurrences	Average Interval (years/occurrence)
Eastern Pacific El Niño	1950–1990	1957–1958, 1965–1966, 1972–1973, 1982–1983, 1986–1987	5	8
	1991–2023	1991–1992, 1997–1998, 2002–2003, 2009–2010, 2015–2016, 2018–2019, 2023–2024	7	4.71
Eastern Pacific La Niña	1950–1990	1950–1951, 1954–1956, 1964–1965, 1970–1971, 1973–1974, 1975–1976, 1988–1989	7	5.71
	1991–2023	1995–1996, 1998–2000, 2007–2008, 2010–2011, 2016–2017, 2020–2021	6	5.5
Central Pacific El Niño	1950–1990	1963–1964, 1968–1969, 1977–1978, 1986–1987	4	10
	1991–2023	1994–1995, 2002–2003, 2004–2005, 2009–2010, 2014–2015, 2018–2019	6	5.5
Central Pacific La Niña	1950–1990	1954–1956, 1956–1957, 1970–1971, 1988–1989	4	10
	1991–2023	1995–1996, 1998–2000, 2007–2008, 2010–2011, 2017–2018, 2020–2022	6	5.5

3.4. Frequency and Intensity of ENSO Events

During El Niño events, sea surface temperatures in the central and eastern equatorial Pacific generally exhibited a significant upward trend. This leads to abnormal warming of the entire tropical Pacific region, subsequently affecting the global climate system. In contrast, during La Niña events, sea surface temperatures in the central and eastern equatorial Pacific generally exhibited a downward trend, resulting in a decrease in sea temperature anomalies and having an opposite impact on the global climate.

This study further compared the frequency and intensity of ENSO events during the periods 1950–1990 and 1991–2023, as well as the proportion changes between multi-year and single-year events.

By comparing the frequency of ENSO events in these two periods, it appears that the frequency of ENSO events increased during 1991–2023. Notably the occurrence frequency of El Niño events was relatively high, which aligns with the current global warming trend along with the increase in SSTAs in the tropical Pacific. This finding is consistent with the results of recent studies, suggesting that the rise in multi-year La Niña events may be linked to changes in the Pacific background state. In particular, stronger warming in the western Pacific can strengthen feedback processes between winds, currents, and the upper ocean. This makes it easier for El Niño events to quickly flip into La Niña conditions that persist for several years [23,24].

In recent years, the changing trend of the ENSO phenomenon has shown more complexity and uncertainty. Since 2000, the intensity and frequency of ENSO events have significantly increased, particularly in the late 2010s. During this period, both El Niño and La Niña events became more frequent, though La Niña slightly outnumbered El Niño. More frequent transitions between the two phases are also observed. Furthermore, under the influence of global warming, the ENSO phenomena has exhibited increased variability which complicates predictions and forecasting.

The analysis indicates that over the past 30 years, the proportion of multi-year events and eastern Pacific events within El Niño occurrences has decreased, while the proportion of single-year events and Central Pacific events has increased. For La Niña events, the

proportion of multi-year events has risen, reflecting changes in the climate patterns of the central and eastern equatorial Pacific region. The frequency and intensity of ENSO events may have changed over the past few decades, potentially influenced by factors such as global climate warming.

4. Summary and Concluding Remarks

This study conducted an analysis of the spatiotemporal variations and characteristics of the El Niño–Southern Oscillation (ENSO) phenomenon from 1950 to 2023, exploring its impacts on the global climate system and its changing trends. The study found that changes in SSTA are significantly influenced by global warming and other factors, showing evident spatiotemporal variation patterns. The frequency and intensity of ENSO events differ across various periods.

Based on the research findings, ENSO events exhibit significant spatial changes. The occurrence proportion and intensity of Central Pacific and Eastern Pacific events have both varied. Over the past few decades, the occurrence of Eastern Pacific events has slightly declined, while that of Central Pacific events has increased. This is correlated with global climate warming and changes in the patterns of ocean circulation in the Pacific. These results further demonstrate that ENSO diversity and spatial asymmetry have intensified since the 1990s, consistent with recent studies [20,21]. The proposed EMI-e index effectively captures these changes by emphasizing the central–eastern Pacific SST gradient, providing a simple yet robust metric for distinguishing ENSO flavors and tracking their evolution. Future studies could further explore the relationship between these spatial changes and different global regions.

In terms of temporal changes, the occurrence and intensity of single-year and multi-year El Niño and La Niña events have also changed. In recent years, the occurrence and intensity of single-year El Niño events have increased, while those of multi-year El Niño events have decreased. On the other hand, the frequency of single-year La Niña events has significantly decreased, while that of multi-year La Niña events has increased. This reflects the evolving nature of ENSO events and their impacts on the global climate system. By quantitatively identifying these temporal transitions, this study contributes to understanding the interdecadal evolution of ENSO behavior and highlights the increasing persistence of La Niña conditions in a warming climate. Future studies could further investigate the mechanisms by which different types of ENSO events affect global climate change.

The impact of ENSO events on sea surface temperatures is one of the critical factors in global climate change. This study found that in recent years, SSTAs have shown a significant warming trend, particularly during El Niño events. Together, these findings underscore the growing role of ENSO in modulating global heat redistribution and its feedback to the climate system.

While this study provides an in-depth analysis of the spatiotemporal changes in the ENSO phenomenon, there are still some limitations. First, this research is based solely on observational data from recent decades, making it difficult to accurately predict long-term trends of ENSO events. Additionally, the study focused primarily on spatial and temporal variations and did not deeply explore the mechanisms driving these changes in relation to the global climate system. Nevertheless, the methodological framework combining ONI, EMI, and EMI-e offers a reproducible diagnostic approach that can support model evaluation and improve ENSO monitoring under future climate scenarios. Future research could employ climate models to study the formation and development mechanisms of ENSO events in greater detail.

Since ENSO events are influenced by various factors, including atmospheric, oceanic, and surface processes, further research is needed to study their interactions with other climate phenomena. Future studies should focus on exploring the relationships between ENSO and other climate drivers by integrating diverse observational data sources and model simulations. Such an approach would deepen our understanding of the complex interactions between ENSO events and global climate change, ultimately enhancing our ability to predict future climate patterns.

Although this study did not investigate the physical mechanisms underlying ENSO variability, the observed spatiotemporal trends still hold significant value for practical applications. In addition, accurate prediction of ENSO trends has important practical implications. ENSO is a key driver of hydroclimate extremes in Southeast Asia, where El Niño often triggers severe droughts and water shortages, while La Niña can lead to excessive rainfall and flooding [25,26]. Anticipating the onset and intensity of these events provides critical lead time for governments and communities to prepare, for example, by strengthening water reservoir management, adjusting agricultural practices, or implementing drought and flood early-warning systems. Integrating ENSO forecasts into regional climate adaptation strategies not only mitigates the impacts of extreme events but also enhances socioeconomic resilience in vulnerable regions. Overall, this research contributes both scientifically and practically: scientifically by advancing ENSO classification and its long-term analysis framework, and practically by providing a diagnostic foundation for climate adaptation and disaster risk reduction under a warming world. This highlights the broader significance of the study in supporting climate change adaptation and disaster risk management.

Author Contributions: Conceptualization, P.-H.W. and C.-R.H.; methodology, P.-H.W. and C.-H.L.; software, P.-H.W. and C.-H.L.; supervision, C.-R.H.; formal analysis, P.-H.W. and C.-H.L.; writing—original draft preparation, P.-H.W. and C.-H.L.; writing—review and editing, C.-R.H., H.C. and L.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by National Science and Technology Council of Taiwan through Grant NSTC 114-2611-M-019-016 and the National Oceanic and Atmospheric Administration (NOAA) through Grant NA24OARX432C0007.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The NOAA Extended Reconstructed Sea Surface Temperature (ERSST) data used in this study are available from the National Centers for Environmental Information (NCEI) at https://doi.org/10.7289/V5T72FNM.

Acknowledgments: The authors would like to acknowledge Luke Taulbee from Colorado State University for his careful proofreading of this manuscript. In addition, due to U.S federal government shutdown, Tony Liao from NOAA Global Systems Laboratory is not listed as a coauthor on this article. But the authors want to acknowledge the contribution of Liao during the development of this article.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Timmermann, A.; An, S.-I.; Kug, J.-S.; Jin, F.-F.; Cai, W.; Capotondi, A.; Wittenberg, A.T.; Yun, K.-S.; Stuecker, M. F.; Chikamoto, Y.; et al. El Niño–Southern Oscillation complexity. *Nature* **2018**, *559*, 535–545. [CrossRef]
2. Cai, W.; McPhaden, M.J.; Grimm, A.M.; Rodrigues, R.R.; Taschetto, A.S.; Garreaud, R.D.; Dewitte, B.; Poveda, G.; Ham, Y.-G.; Santoso, A. Climate impacts of the El Niño–southern oscillation on South America. *Nat. Rev. Earth Environ.* **2020**, *1*, 215–231. [CrossRef]

3. Cai, W.; Wang, G.; Santoso, A.; McPhaden, M.J.; Wu, L.; Jin, F.-F.; Timmermann, A.; Collins, M.; Vecchi, G.; Lengaigne, M. Increased frequency of extreme La Niña events under greenhouse warming. *Nat. Clim. Change* **2015**, *5*, 132–137. [CrossRef]
4. Davey, M.K.; Brookshaw, A.; Ineson, S. The probability of the impact of ENSO on precipitation and near-surface temperature. *Clim. Risk Manag.* **2014**, *1*, 5–24. [CrossRef]
5. Ding, Y.; Liu, Y.; Liang, S.; Ma, X.; Zhang, Y.; Si, D.; Liang, P.; Song, Y.; Zhang, J. Interdecadal variability of the East Asian winter monsoon and its possible links to global climate change. *J. Meteorol. Res.* **2014**, *28*, 693–713. [CrossRef]
6. McPhaden, M.J.; Zebiak, S.E.; Glantz, M.H. ENSO as an Integrating Concept in Earth Science. *Science* **2006**, *314*, 1740–1745. [CrossRef]
7. Wang, B.; Wu, R.; Fu, X. Pacific–East Asian teleconnection: How does ENSO affect East Asian climate? *J. Clim.* **2000**, *13*, 1517–1536. [CrossRef]
8. Yang, S.; Li, Z.; Yu, J.-Y.; Hu, X.; Dong, W.; He, S. El Niño–Southern Oscillation and its impact in the changing climate. *Natl. Sci. Rev.* **2018**, *5*, 840–857. [CrossRef]
9. Stenseth, N.C.; Mysterud, A.; Ottersen, G.; Hurrell, J.W.; Chan, K.-S.; Lima, M. Ecological effects of climate fluctuations. *Science* **2002**, *297*, 1292–1296. [CrossRef]
10. Ropelewski, C.F.; Halpert, M.S. Global and regional scale precipitation patterns associated with the El Niño/Southern Oscillation. *Mon. Weather Rev.* **1987**, *115*, 1606–1626. [CrossRef]
11. Chen, Y.; Liu, J.; Zhang, Y.; Li, X. Analysis of ENSO event intensity changes and time–frequency characteristics since 1875. *Atmosphere* **2024**, *15*, 1428. [CrossRef]
12. Ashok, K.; Behera, S.K.; Rao, S.A.; Weng, H.; Yamagata, T. El Niño Modoki and its possible teleconnection. *J. Geophys. Res. Ocean.* **2007**, *112*, C11. [CrossRef]
13. Kao, H.-Y.; Yu, J.-Y. Contrasting Eastern-Pacific and Central-Pacific Types of ENSO. *J. Clim.* **2009**, *22*, 615–632. [CrossRef]
14. Trenberth, K.E.; Stepaniak, D.P. Indices of El Niño evolution. *J. Clim.* **2001**, *14*, 1697–1701. [CrossRef]
15. Larkin, N.K.; Harrison, D. On the definition of El Niño and associated seasonal average U.S. weather anomalies. *Geophys. Res. Lett.* **2005**, *32*, L13705. [CrossRef]
16. Climate Prediction Center, NOAA. ONI—Oceanic Niño Index. NOAA National Weather Service. Available online: https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php (accessed on 23 December 2024).
17. Huang, B.; Thorne, P.W.; Banzon, V.F.; Boyer, T.; Chepurin, G.; Lawrimore, J.H.; Menne, M.J.; Smith, T.M.; Vose, R.S.; Zhang, H.-M. Extended reconstructed sea surface temperature, version 5 (ERSSTv5): Upgrades, validations, and intercomparisons. *J. Clim.* **2017**, *30*, 8179–8205. [CrossRef]
18. Kennedy, J.J.; Rayner, N.A.; Smith, R.O.; Parker, D.E.; Saunby, M. Reassessing biases and other uncertainties in sea surface temperature observations measured in situ since 1850: 2. Biases and homogenization. *J. Geophys. Res. Atmos.* **2011**, *116*, D14103. [CrossRef]
19. Hausfather, Z.; Cowtan, K.; Clarke, D.C.; Jacobs, P.; Richardson, M.; Rohde, R. Assessing recent warming using instrumentally homogeneous sea surface temperature records. *Sci. Adv.* **2017**, *3*, e1601207. [CrossRef]
20. Li, X.; Yu, J.Y.; Ding, R. El Niño-La Niña asymmetries in the changes of ENSO complexities and dynamics since 1990. *Geophys. Res. Lett.* **2024**, *51*, e2023GL106395. [CrossRef]
21. Yeh, S.-W.; Kug, J.-S.; Dewitte, B.; Kwon, M.-H.; Kirtman, B.P.; Jin, F.-F. El Niño in a changing climate. *Nature* **2009**, *461*, 511–514. [CrossRef]
22. Cai, W.; Cowan, T.; Sullivan, A. Recent unprecedented skewness towards positive Indian Ocean Dipole occurrences and its impact on Australian rainfall. *Geophys. Res. Lett.* **2014**, *36*, L11705. [CrossRef]
23. Wang, C.; Deser, C.; Yu, J.-Y.; DiNezio, P.; Clement, A. El Niño and Southern Oscillation (ENSO): A review. In *Coral Reefs of the Eastern Pacific. Coral Reefs of the World*; Glymn, P., Manzello, D., Enochs, I., Eds.; Springer: Dordrecht, The Netherlands, 2016; Volume 8, pp. 85–106.
24. Wang, B.; Sun, W.; Jin, C.; Luo, X.; Yang, Y.-M.; Li, T.; Xiang, B.; McPhaden, M.J.; Cane, M.A.; Jin, F. Understanding the recent increase in multiyear La Niñas. *Nat. Clim. Change* **2023**, *13*, 1075–1081. [CrossRef]
25. Phan-Van, T.; Nguyen-Ngoc-Bich, P.; Ngo-Duc, T.; Vu-Minh, T.; Le, P.V.; Trinh-Tuan, L.; Nguyen-Thi, T.; Pham-Thanh, H.; Tran-Quang, D. Drought over Southeast Asia and its association with large-scale drivers. *J. Clim.* **2022**, *35*, 4959–4978. [CrossRef]
26. Naylor, R.L.; Battisti, D.S.; Vimont, D.J.; Falcon, W.P.; Burke, M.B. Assessing risks of climate variability and climate change for Indonesian rice agriculture. *Proc. Natl. Acad. Sci. USA* **2004**, *104*, 7752–7757. [CrossRef] [PubMed]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.