

History, Mechanisms, and Future Directions of the El Niño-Southern Oscillation under the Severe Climate Change

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Abstract. The El Niño-Southern Oscillation is a global occurrence that arises from the interplay between air and ocean. It is characterized by three distinct phases: neutral, El Niño, and La Niña. These phases have varying effects on the global climate. Given the rapid changes in the world's climate, ENSO's role as a climate predictor is becoming increasingly vital. This article aims to provide an overview of ENSO research, including its history and present status. It also delves into the mechanisms behind ENSO and the different indicators used to anticipate its behaviour, as well as its effects on China's climate and the human populace. Furthermore, the article explores future research directions, emphasizing the importance of addressing issues such as optimal precursors and barriers to spring predictability to achieve better ENSO predictability. The ultimate goal is to improve the accuracy and precision of forecasts, enabling humans to cope better with unforeseen climate changes.

Keywords: ENSO, ENSO Proxy Indices.

1. Introduction

The El Niño-Southern Oscillation, commonly referred to as ENSO, is defined by alternating phases of El Niño and La Niña in the ocean, which are in tandem with the Southern Oscillation occurring in the atmosphere. El Niño is characterized by an abnormal increase in the temperature of the equatorial eastern Pacific Ocean, whereas the Southern Oscillation depicts the varying sea level pressures throughout the Indian and Pacific Oceans. ENSO holds the distinction of being the only verified global oscillation, serving as a powerful indicator of the interconnectedness of the global atmosphere and ocean systems. It plays a pivotal role in shaping the climatic conditions in numerous regions around the world. [1,2].

The cycle of ENSO is segmented into three primary stages: the Neutral, El Niño, and La Niña phases. The Neutral stage, also referred to as the Walker circulation, is marked by the eastward displacement of warmer waters in the eastern equatorial Pacific, propelled by the easterly trade winds. This process gives rise to the Western Pacific Warm Pool (WPWP), a region distinguished by reduced Sea Surface Temperatures (SSTs) resulting from the influence of the cold Peru Current and the prevailing trade winds. Figure 1 offers a visual representation of this stage, showcasing the prevalent circulation and the distribution of sea temperatures under standard conditions [3,4].

December - February Normal Conditions

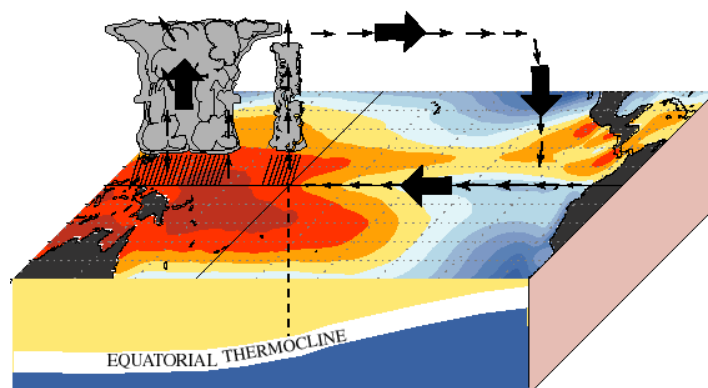


Fig. 1 The Circulation and Sea Temperature Distribution under Normal Conditions.

(Source: https://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensocycle/meanrain.shtml)

During the El Niño phase, weakened trade winds hinder the westward accumulation of warm water in the equatorial eastern Pacific, reversing the Walker circulation. Conversely, the La Niña phase strengthens the Walker circulation, enhancing the easterly trade winds and cooling the waters in the equatorial eastern Pacific. These oscillations have profound implications on global weather patterns, inducing droughts, wildfires, and even cyclonic activities in various regions [5].

Recent studies have emphasized the critical role of understanding ENSO dynamics in enhancing forecasting and prediction capabilities. Leveraging models such as the oceanographic and recharge oscillator models, scientists can anticipate the periodic variations of SST and thermocline depth in the central equatorial Pacific Ocean, facilitating informed policy implementation to mitigate environmental impacts [6-8].

In this study, we delve deeper into the intricate dynamics of ENSO, exploring its history, mechanisms, and potential future trajectories under severe climate change scenarios. Drawing from a rich array of data and leveraging advanced predictive models, we aim to shed light on the evolving patterns of ENSO and its implications on global climate patterns. By fostering a comprehensive understanding of ENSO, we aspire to contribute to the global efforts in enhancing climate resilience and fostering sustainable environmental management strategies for the future. Our research not only stands as a testament to the scientific community's advancements in understanding this complex phenomenon but also serves as a beacon guiding policy formulations to safeguard our environment for future generations [9,10].

2. History of ENSO Research

The initial observations of the El Niño phenomenon can be traced back to the early 19th century when Peruvian fishermen recognized a warm coastal current elevating seawater temperatures during the winter season. Around the same period, Sir Gilbert Walker discerned the "Southern Oscillation," a notable fluctuation in the sea level pressure across Indonesia and the tropical Pacific, albeit without realizing its connection to the El Niño events or Pacific alterations. It was not until the late 1960s that Jacob Bjerknes, among others, formulated the term "ENSO" upon observing the interconnected dynamics of the oceanic and atmospheric changes, thereby bringing the concepts of "El Niño" and "La Niña" to the forefront [3,11].

Over the ensuing decades, extensive research has been undertaken to unravel the intricacies of ENSO, with substantial advancements occurring in the 1980s and 1990s [12,13]. The 1997-1998 El Niño event heightened global curiosity in ENSO, catalyzing increased funding in research and predictive efforts [14]. This scholarly pursuit has fostered the creation of seasonal climate prognostic models and enhanced comprehension of its repercussions on human societies. ENSO embodies a multifaceted system characterized by ocean-atmosphere interactions, with the "Southern Oscillation" delineating the atmospheric facet involving air pressure alterations over the tropical Pacific Ocean. The sustained emphasis on research and forecasting endeavors serves to alleviate the adverse effects of such phenomena, safeguarding susceptible communities globally. The exploration of ENSO remains pivotal in decoding worldwide climate fluctuations, facilitating preparedness against the potential impacts on human habitats through the inception of seasonal climate forecast models.

3. Current State of ENSO Research

ENSO has been the subject of comprehensive research by scientists who employ a range of indices to decipher its underlying mechanisms and forecast its patterns. A pivotal element in this field of study involves the assessment of anomalies in sea surface temperatures (SSTA) and variations in atmospheric pressure. Predominantly utilized ENSO indices encompass Niño4, Niño3.4, Niño3, and Niño1+2, which are instrumental in determining the severity and geographical occurrence of ENSO events [15,16]. The Oceanic Niño Index (ONI), standing as the preeminent index in this domain,

calculates the three-month rolling average of SST anomalies within the Niño 3.4 region. The initiation of El Niño or La Niña phases is acknowledged when the ONI surpasses or falls below a threshold of ± 0.5 degrees Celsius.

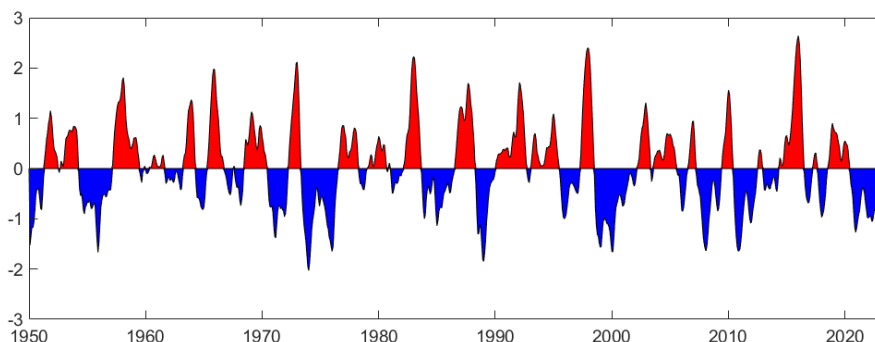


Fig. 2 ONI from DJF 1950 to MJJ 2023. Red represents El Niño years and blue represents La Niña years.

(Source: <https://www.cpc.ncep.noaa.gov/data/indices/oni.ascii.txt>)

Over time, scientists have evolved their use of indices, incorporating atmospheric pressure oscillations as a measure of ENSO. In the past, the Southern Oscillation Index (SOI) was used to describe these oscillations, determined by the difference in sea level pressure (SLP) between Tahiti and Darwin [17].

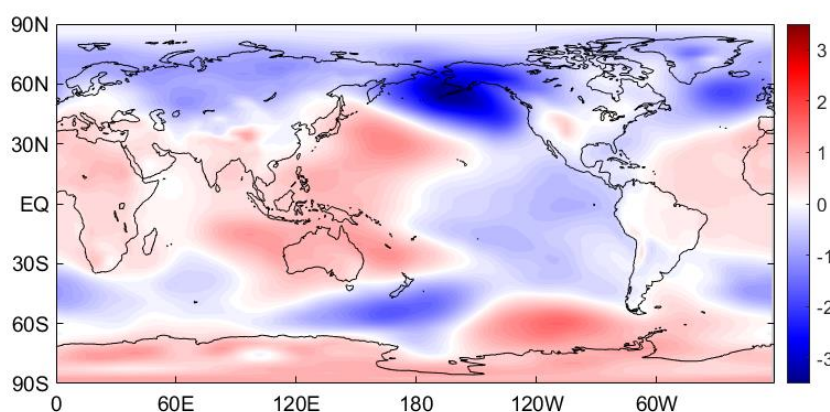


Fig. 3 Distribution of Sea Level Pressure Anomalies under El Niño Conditions.

(Source: <http://www.psl.noaa.gov/data/gridded/data.ncep.reanalysis.derived.html>)

However, scientists have recently explored new indices, such as the Equatorial SOI (EQSOI), which better characterizes ENSO [14]. EQSOI measures the sea level pressure contrast in the equatorial Pacific and shows promise in improving ENSO prediction models and understanding its impact on global climate patterns. In addition, the Modoki index and the warm pool and cold tongue indices represent central and eastern Pacific ENSO, respectively [18,19].

Among the myriad impacts of ENSO on the climatic conditions in China, two significant effects will be elaborated upon in the subsequent sections. The initial aspect pertains to the temperatures experienced in the winter season. Research conducted by Dong and Liu [20] indicates a positive correlation between El Niño and La Niña phenomena and the wintertime temperatures in China. Specifically, the El Niño periods are characterized by warmer winters, whereas the La Niña phases bring about colder conditions. The second focal point is the influence of ENSO on the commencement of the South China Sea summer monsoon (SCSSM). ENSO exhibits a predictive capacity in this regard, with El Niño years generally causing a delayed onset of SCSSM, in contrast to La Niña years which tend to usher in an earlier commencement [21].

The occurrence of ENSO events can impact climate and have subsequent effects on human beings. There are several ways in which this can occur. Firstly, ENSO can cause either drought or

precipitation, which in turn affects agricultural water use and reduces food production. This can affect the transportation routes for grain and further impact agriculture. Secondly, ENSO can also affect marine ecosystems by altering sea temperatures, which can impact the water cycle and ocean currents. This can interrupt the food chain of aquatic organisms and result in an insufficient food supply for coastal populations. Finally, ENSO can also create conditions for new diseases to emerge by altering precipitation and humidity [22]. For instance, the El Niño phenomenon increases humidity through rainfall, creating favorable conditions for mosquitoes and leading to the spread of malaria.

4. Future Directions in ENSO Research

ENSO research primarily focuses on its predictability, which can be divided into two categories: “Optimal Precursors” and “Spring Predictability Barriers” (SPB). The application of the CNOP concept to the ENSO forecasting issue was demonstrated in Mu et al.'s study using a straightforward ocean-atmosphere coupling model [23]. According to the findings, CNOP is more effective than LSV at identifying the initial mode that will most likely develop into an El Niño or La Niña event. Based on the nonlinear oscillation the model depicted, they discussed the physical mechanism of the ideal ENSO predecessors.

SPB mechanism is dependent on three factors: instability in ocean-atmosphere coupling during spring, dynamic instability and weak persistence of El Niño during spring, and the initial error of El Niño's development following the same growth mechanism as the actual event during spring [24]. Meng et al. found that there is a strong correlation between the entropy of each year and the intensity of El Niño in the next year [25]. The method based on this information entropy advances the ENSO forecast period by half a year, which allows people to judge the occurrence of ENSO events earlier. Significantly extending the warning time can significantly reduce the losses caused by meteorological disasters caused by ENSO.

After that, Chen et al. used the residual neural network and pure observations to improve the forecast of ENSO. This model can alleviate the problems caused by SPB, and the automatically selected optimal precursor can explain the impact of dynamic processes on ENSO changes [26].

5. Conclusion

In light of the relentless endeavors of the scientific community, there has been a remarkable advancement in the comprehension of the ENSO phenomenon. The inception of this trajectory can be traced back to the rudimentary observations of Peruvian fishermen who identified the warm coastal current, thereby sowing the seeds for a rich tapestry of research that spans several decades. The contemporary understanding of ENSO is characterized by a deep-seated knowledge of its intricate dynamics, facilitated by the development of sophisticated tools designed to mitigate its adverse impacts on human societies. It is unequivocal that fluctuations in the sea SST associated with ENSO exert a profound influence on the global climate system.

As we navigate through an era marked by escalating global warming, there is a discernible increase in the frequency of El Niño events, a trend that diverges significantly from the projections delineated in the sixth report of the Intergovernmental Panel on Climate Change (IPCC). Furthermore, there is a burgeoning diversity in the manifestations of ENSO events, a phenomenon that stands in stark contrast to earlier anticipations. In the face of the current IPCC plausible emission scenarios, it is projected that the variability in ENSO SST could persist for centuries, a forecast grounded in empirical evidence. This underscores the imperative for heightened awareness and understanding of the evolving dynamics of ENSO within the global populace.

To foster a future where societies are resilient to the changing climate, it is incumbent upon the scientific fraternity to recalibrate existing models to enhance the accuracy of ENSO predictions. This endeavor necessitates a collaborative approach, leveraging the collective intelligence and expertise

of researchers globally, to steer humanity towards a path of informed preparedness and adaptive response to the multifaceted challenges posed by ENSO variability.

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