ENSO in a warming climate: the relative Niño 3.4 index

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Abstract: The traditional Niño 3.4 index has been losing precision and credibility in recent years, fundamentally due to the increase in global warming. El Niño 2023/24 was expected to be one of the strongest ones, however it resulted to be weaker. This error in the prediction could be associated with the use of the traditional Niño 3.4 index, which does not take global warming into account. Therefore, this thesis has assessed the advantages of using the relative Niño 3.4 index. Observational data using winter means (DJF) over 1950-2024 have been employed. The results suggested that it is increasingly necessary to rely more on the relative index rather than the traditional one. As shown in the study, the former takes into account and reduces the influence of global warming, which was probably the main reason of the incorrect forecast.

I. INTRODUCTION

The phenomenon of El Niño is one of the largest and most investigated climate oscillations globally because it has far-reaching implications for global climate. The El Niño is characterized by an occurrence of SST anomalies over the eastern tropical Pacific Ocean in the specific region known as Niño 3.4 (5°N-5°S, 170°W-120°W, shown in Figures 3 and 4). A better comprehension of El Niño remains critical to predicting and managing its effects on climatic and socioeconomic systems.

This natural phenomenon corresponds to the warm phase of the natural cycle known as the El Niño-Southern Oscillation (ENSO). It presents a heating up on surface waters within the central and eastern equatorial Pacific. This warming alters atmospheric and oceanic circulation patterns resulting in important alterations in climate conditions including precipitation changes, extreme temperatures or occurrence of extreme weather phenomena such as droughts or floods [1].

In this study we have chosen DJF (December-January-February), when ENSO attains its maximum phase.

To understand El Niño, one of the most important things to do is to analyze climatology (Figure 1) and variability (Figure 2) of SSTs. In Figure 1, it is seen that the warmest temperatures are mainly located in the western equatorial Pacific and Indian ocean specifically in an area called Maritime Continent. Furthermore, this region because of high SSTs also shows maximum climatological precipitation [1].

In contrast, colder waters are found in the eastern equatorial Pacific, in the region known as the "cold tongue". This area, with very low temperatures, has minimal precipitation. This SST distribution is explained by the trade winds blowing from east to west, accumulating warm surface waters in the west and facilitating the upwelling of cold deep waters in the east.

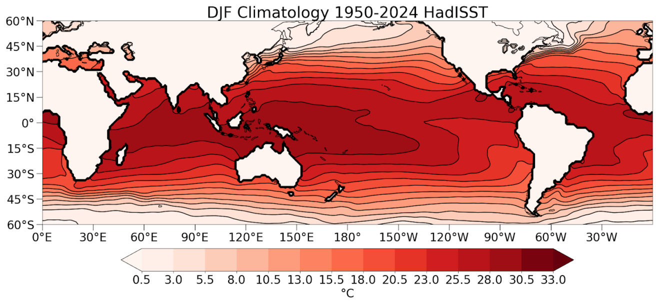

FIG. 1: SST climatology in DJF computed on the seasonal mean field from 1950 to 2024. Warmest temperatures are located in the western equatorial Pacific and Indian Ocean, while the coldest temperatures inside the tropical Pacific define the cold tongue region.

The SST standard deviation (Figure 2) shows the interannual variability of SST, highlighting areas where temperatures vary significantly from year to year [2]. The Niño 3.4 region shows high values of standard deviation, indicating large fluctuations between El Niño years (when the "cold tongue" warms anomalously) and La Niña years (when it cools even further than climatology). During an El Niño event, the anomalous warming in the "cold tongue" shifts precipitation eastward, affecting global climate patterns. In contrast, during La Niña, the "cold tongue" cools significantly, reducing precipitation in this region and further increasing it over the Maritime Continent, where it is located in neutral conditions [3].

The Niño 3.4 index, based on SST anomalies in the central Pacific region, has been fundamental for monitoring and predicting these events. However, with the increasing impact of global warming, the effectiveness of this index has been questioned. The widespread increase in SST has altered the baseline characteristics of the Niño 3.4 region, making traditional anomalies less representative of the conditions related to El Niño and La Niña events.

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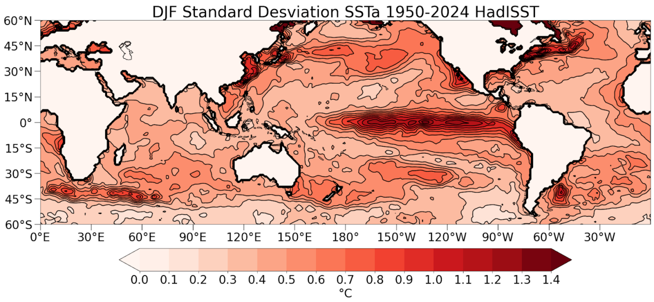

FIG. 2: SST standard deviation in DJF showing the variability associated to temperatures from 1950 to 2024. The highest variations correspond to Niño 3.4 region, reaching the west coast of South America.

Given that global warming affects different ocean regions unevenly, it is crucial to develop new indices that account for these changes. These new indices must be able to distinguish between general global warming and specific variations indicating the presence of El Niño. The relative Niño 3.4 index emerges as an innovative solution [4]. This new index is based on relative SST anomalies, adjusting the calculation to account for the background warming induced by climate change in the tropical band (20°S-20°N).

II. DATA AND METHODOLOGY

In this study, two datasets have been used, the Extended Reconstructed Sea Surface Temperature (ERSST) [5] dataset and the Hadley Centre Sea Ice and Sea Surface Temperature (HadISST) [6] dataset, to contrast results and evaluate observational uncertainty. Several diagnostics have been computed: climatology (the mean), variability (the standard deviation), linear trends, weights of each value based on latitude and the calculation of the new index. These procedures will be explained in detail in this section. For all computations we consider the period 1950-2024.

To calculate climatology (essential for visualizing temperature distribution in Figure 1 and subsequently calculating the indices), the mean of each geographic SST value during those years was taken, resulting in a climatological value for each grid point on the map.

$$\text{clim} = \frac{\sum_{i=1}^{N} SST_i}{N} \tag{1}$$

where N are the total number of years.

Similarly, variability was calculated by simple standard deviation of SST values for each grid point.

$$\sigma_{SST} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(SST_i - \bar{SST})^2} \tag{2}$$

Before moving on to the correct calculation of the N34 index (with weights), the anomalies must be calculated by subtracting the climatology.

$$\text{anom} = SST - \text{clim} \tag{3}$$

Now, an essential step for an optimal index calculation is determining the distribution of weights for each value based on its geographical position (latitude). As the Earth is not flat, each SST value occupies a different area on the Earth's surface. Therefore, a proper weight for each value is necessary when calculating indices.

To achieve this, the cosine of each latitude was calculated to determine the weight.

$$w_j = \cos\left(\frac{lat_j \cdot \pi}{180}\right) \tag{4}$$

which was then multiplied by each anomaly value:

$$\text{anom}_{w_j} = w_j \times \text{anom}_j \tag{5}$$

Finally, to calculate the N34 index value, the following calculation was carried out to culminate with spatial averaging:

$$N34 = \frac{\sum_{j=1}^{M} \text{anom}_{w_j}}{\sum_{j=1}^{M} w_j} \tag{6}$$

where M represents the total number of different values in a determinated region (in our study, the Niño 3.4).

It must be clarified that we have used N34 to refer to this region, but other indices could also be used depending on the region chosen.

Finally, once we can calculate these indices, we describe the calculation of the relative N34 index, which relates the traditional N34 index to the tropical mean, according to [7].

$$\text{Relative N34} = \frac{1}{N}\sum_{i=1}^{N}(N34 - TropAve)\frac{\sigma_{N34i}}{\sigma_{(N34-TropAve)_i}} \tag{7}$$

As can be seen in the calculation procedure, what differentiates the two indices is that the relative index captures the global warming signal (which we are not interested in for this index). Thus, the new index solely reflects the variability associated with ENSO. For this reason, in recent years, N34 > relative N34, since the relative index does not account for the global warming that has been increasing in recent years. Using the new index, we can reassess whether it will be a strong or weak El Niño, as it will not have the additional warming associated with the global trend.

III. RESULTS

A. Evidence of Global Warming

ERSST and HadISST analysis datasets suggest that SSTs have been rising steadily since the 1950s. These maps (Figures 3 and 4) which are SST linear trends based on data from these datasets, visually depict the areas of the globe that have encountered temperature increases since 1950. The least trend is found in Niño 3.4 area while a high trend is seen in other parts due to global warming.

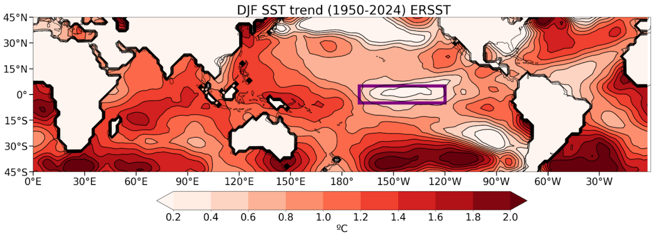

FIG. 3: SST linear trend DJF computed on from 1950 to 2024 with ERSST.

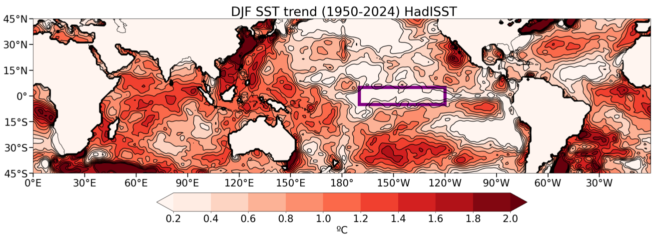

FIG. 4: SST linear trend DJF computed from 1950 to 2024 with HadISST database.

B. Justification of the Study

The objective of this research is to assess and apply the relative Niño 3.4 index in monitoring El Niño, especially for the event of 2023/2024. Moreover, this paper will consider how global warming affects the effectiveness of the traditional index. Figures 5 and 7 comparing the Niño 3.4 index with and without trend reveal a less pronounced trend in the traditional Niño 3.4 index than Tropical Mean Index in Figures 6 and 8. This low trend is potentially due to substantial SST variability within the El Niño 3.4 region; it occurs as a result from alternating La Niña and El Niño events where global warming becomes indistinguishable.

On the other hand, the evolution of the tropical band shows a marked positive trend (Figures 6 and 8). This stronger warming rate is probably associated with the regional warming trend in the tropical Atlantic and over the Maritime Continent (Figures 3 and 4).

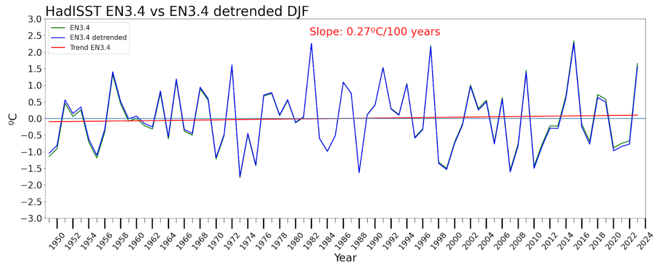

FIG. 5: SST N34 in DJF with and without trend from 1950 to 2024 with HadISST. It is also shown the corresponding slope (red line) which is very slight and informs us about the low trend in this region. However, also this trend gives us insight about the global warming.

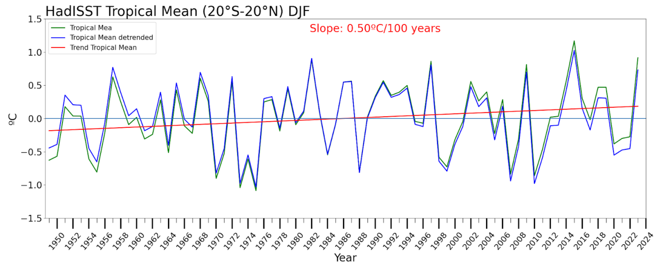

FIG. 6: SST Tropical Mean in DJF with and without trend from 1950 to 2024 with HadISST. The corresponding slope (red line) is higher, informing us about the strong global warming signal in this region and their influence in this index.

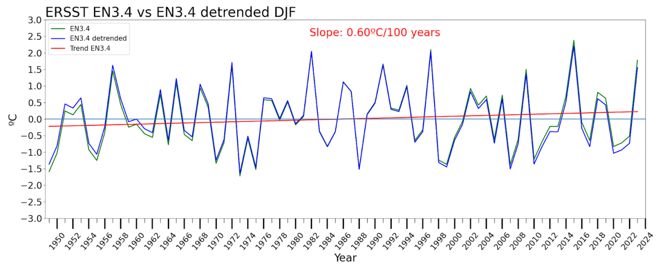

FIG. 7: SST N34 in DJF with and without trend from 1950 to 2024 with ERSST. It is also shown the corresponding slope (red line) which is very slight and informs us about the low trend in this region. However, this low trend gives us insight about the global warming.

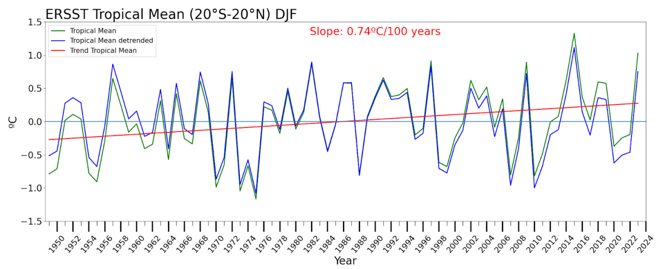

FIG. 8: SST Tropical Mean in DJF with and without trend from 1950 to 2024 with ERSST. The corresponding slope (red line) is higher, informing us about the strong global warming signal in this region and their influence in this index.

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Each Figure must be compared with the one from the same dataset to obtain consistent results. For this reason, it is strictly necessary to find another index that eliminates that trend related to global warming to have a more representative index for the current evolution of ENSO.

In Figures 5, 6, 7, and 8, the need to use a new index that takes into account global warming has been shown.

C. Comparison of the traditional Niño 3.4 and the relative Niño 3.4 indices

In this section, the difference between the two Niño 3.4 indices from 1950 to 2024 has been assessed. As shown in Figures 9 and 10, this difference has become more positive over the years, strongly demonstrating the aforementioned impact of global warming. Figure 9 shows a slight positive trend in the traditional N34 index due to global warming (Figures 5 and 7), while the relative index does not exhibit this trend.

In particular, the year 2023/24 stands out as the second year with the largest positive difference between the traditional Niño 3.4 index and the relative Niño 3.4 index as can be seen clearly in Figure 10, with a difference of 0.44°C. This fact further emphasizes the importance of adopting the relative index in current climate analysis and forecasting. It is clearly evident the continuous global warming signal, reflected in the fact that initially the difference between both indices was negative, and in recent years, it has been positive and increasingly larger.

This difference will keep likely increasing in the following years, due to a stronger global warming. For this reason, it is important to start using this index as the most reliable one to have an updated view of the phenomenon.

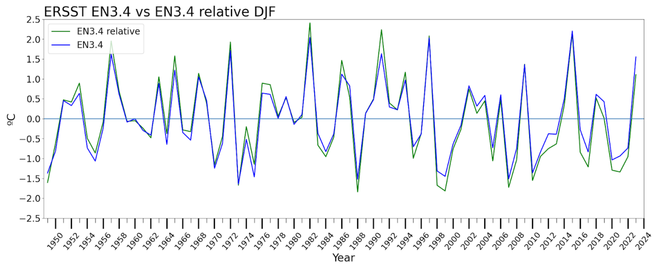

FIG. 9: Traditional N34 and relative N34 in DJF showing their corresponding differences between them from 1950 to 2024 with ERSST. The positive difference is increasing over the years, giving us insight about the importance of taking into account the global warming in the Tropical region.

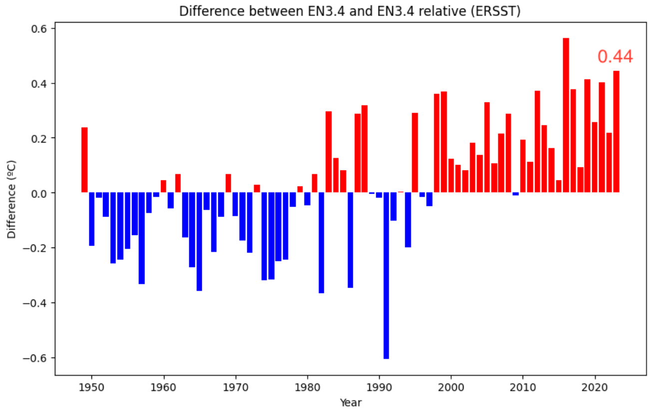

FIG. 10: Difference between traditional N34 and relative N34 in DJF, with ERSST, illustrating the increase of positive discrepancies over the years, due to global warming. It is remarked the 2023/24 event, which corresponds to the second highest value.

D. The 2023/24 El Niño

Now that we have established these foundations, it's time to delve into a more detailed analysis of the 2023/24 year. Despite expectations of a very strong El Niño event, the observed results show that it has not been as powerful as anticipated. Failing to properly account for the index can lead to a mistaken assessment of the strength and magnitude of climatic events, underscoring the importance of employing appropriate and sensitive tools, such as the relative Niño 3.4 index, for accurate evaluation of El Niño and La Niña events.

As seen in Figures 11 and 12, the El Niño event of 2023/2024 has been considerably more moderate compared to the average of the three largest El Niño events recorded, which occurred in 1982/83, 1997/98, and 2015/16 (which was surprising for the scientific community [8]). The SST maps show that the temperature anomalies in 2023/2024 did not reach the extreme levels that characterized the super El Niño events. It is remarkable the big difference between both graphs in the zonal gradient in the Pacific Ocean.

The fact that the 2023/24 event (Figure 11) was not as significant as expected is probably due to what we observe in Figure 10: the global warming signal. This result led us to believe that based on the traditional Niño 3.4 index (which does not take this global warming into account), it was going to be one of the strongest events ever seen. However, using the relative Niño 3.4 index (which does take global warming into account), we would have seen that it was not going to be as strong.

In the years of the three super El Niño events, SSTs in the equatorial Pacific showed strong increases, with positive anomalies widely extending across the Pacific Ocean.

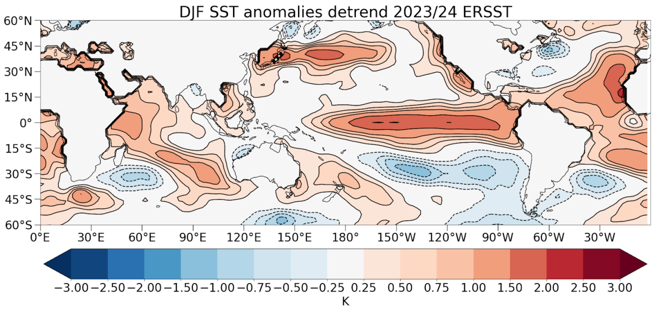

FIG. 11: Detrended SST anomalies in DJF of the event 2023/24 from 1950 to 2024 with ERSST. It illustrates the El Niño event but with slight values than what was expected. The warmest temperatures are located over the Niño region.

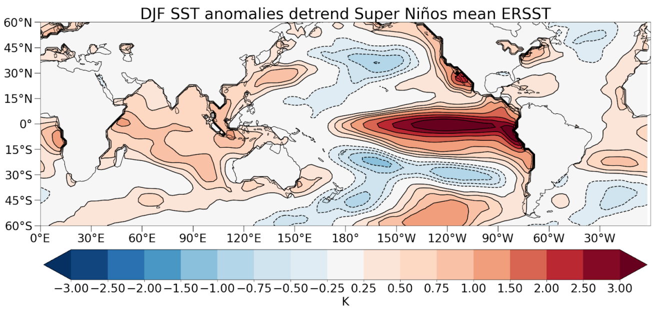

FIG. 12: Detrended SST anomalies in DJF with ERSST, for the three Super El Niños *Super Niños* that have been registered. It can be seen the very high temperatures in the Niño region, that are much stronger than a normal Niño event or than the 2023/24 one.

IV. CONCLUSIONS

This study has assessed the El Niño phenomenon, focusing on the 2023/2024 period and the need to use the relative Niño 3.4 index for a more accurate prediction in the context of global warming.

The analysis has shown that the conventional Niño 3.4 index, that is based on temperature anomalies in a region of the equatorial Pacific, is not enough to capture the effects of global warming. The strength of ENSO events might be affected by the global warming signal.

According to the results, the relative Niño 3.4 index provides a more accurate assessment of El Niño events. This index has proven to be more sensitive to climatic changes and offers a more realistic representation of current conditions.

The study of the 2023/2024 El Niño event has revealed that, although important, it did not reach the expected magnitude suggested by the conventional index. However, when applying the relative Niño 3.4 index, a greater alignment with the observed amplitude was evident. The SSTs anomalies indicate that the event was moderate compared to the super El Niños of 1982/83, 1997/98, and 2015/16 and also that it was superimposed on the global warming signal.

In conclusion, it has been demonstrated that it is really important to start using this new relative index in order to have a more realistic view of the strength of El Niño o La Niña events, avoiding, like this, the global warming effect.

Acknowledgments

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