Testing the robustness of El Niño flavors

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Abstract: The variability of the warm-phase events of the El Niño-Southern Oscillation phenomenon has been under the microscope for the past few decades, with some authors proposing the existence of different types, called *flavors*, of El Niño events. Here we give an overview of the literature concerning spatial patterns of the sea surface temperature anomalies in the equatorial Pacific and the flavors of El Niño. We also use Monte Carlo re-sampling with replacement to examine whether there are significant differences among two flavors of El Niño as defined by one criterion in particular and touch on the possible classification of the most recent 2015-16 event.

I. INTRODUCTION

ENSO is the acronym used to designate the coupling between oscillating sea-level pressure dipole pattern over the tropical Pacific ocean (Southern Oscillation) and the periodic appearance of sea-surface temperature anomalies in the equatorial Pacific region and along the Peruvian coast (El Niño). The two extremes of the oscillatory ENSO cycle are known as El Niño and La Niña and are characterized, respectively, by anomalously warm or cold SST values in the central and eastern equatorial Pacific.

The current average climate of the tropics may be described as a stable system in which each of the dynamic processes controlling the atmospheric pressure, zonal wind circulation, marine upwelling, sea-surface temperatures and precipitation patterns reinforces the others via various coupled feedback mechanisms [1]. ENSO episodes occur when the equilibrium state of the tropical climate is broken by atmospheric or oceanic perturbations which cause those feedback processes to act in reverse (El Niño) or enhance them (La Niña). This results in both tropical and extratropical impacts: temperatures in the tropical Pacific ocean have an influence in the global pattern of atmospheric circulation and, consequently, they have effects on the atmospheric conditions of extratropical locations.

No two El Niños are the same: each event has its unique spatial pattern of SST anomalies, both in extension and in intensity. Some authors attribute certain differences observed in these anomaly patterns to the existence of different types, or "flavors", of El Niño.

This work will focus on the spatial patterns of the Pacific sea-surface temperature (SST) anomalies associated to El Niño episodes and the ongoing discussion over the existence of so-called flavors of ENSO. Section II offers a general overview of the ENSO phenomenon as background, while Section III shifts the focus to the flavors of El Niño, delving into the origin and evolution of the concept. In section IV, we apply our own statistical analysis to test whether the flavors as defined by one particular criterion exhibit statistically significant differences in their SST patterns. Lastly, Section V briefly examines the characteristics of the recent 2015-16 El Niño event in the context of the flavor paradigm.

In our statistical analysis and plots we make use of the NOAA ERSST V4 dataset provided by the National Oceanic and Atmospheric Administration, Physical Sciences Division (Boulder, Colorado, USA), from their website at `http://www.esrl.noaa.gov/psd/`.

II. ENSO: A GENERAL OVERVIEW

The tropical Pacific thermocline is a key element in the changes in SST seen during an El Niño event. The thermocline is a thin layer of ocean water with a very steep vertical temperature gradient, which marks the separation between warm surface water and cold deep water. Under normal circumstances, air ascends over the warm waters of the western tropical Pacific, and cools as it travels aloft toward the eastern Pacific. The now denser air descends, causing the surface pressure in the eastern area to be higher than in the western area, which makes surface winds flow from east to west. This is called Walker circulation, and these easterly surface winds are known as trade winds. The trade winds displace surface water to the west, making the upper layer of warm water much shallower in the eastern Pacific than in the western Pacific. They also cause a poleward flow of the upper layer of water near the equator, forcing the upwelling of cold deep water. This is the reason for the relatively lower SST in that region, known as the Pacific "cold tongue".

The weakening or even reversal of the trade winds and, therefore, of the marine currents causes a flattening of the thermocline and a decrease in the upwelling, which results in a warming of the surface waters east of the Date Line. The positive feedback between the weakening of the trade winds, the decrease in the east-west pressure gradient and the changes in sea-surface temperature maintains the growth of El Niño. The region where these SST anomalies are present is typically divided in four area boxes, as shown in Fig.(1).

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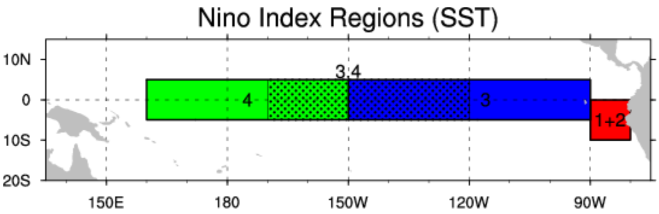

FIG. 1: Map of the four commonly used Niño regions in the Pacific ocean. Source: [2].

One widely used criterion to idenfity what constitutes an El Niño event is the NOAA definition, which is based on the Oceanic Niño Index (ONI): the 3-month running mean of area-averaged SST anomalies in the Niño3.4 region seen in Fig.(1). An El Niño episode is said to have taken place if the ONI exceeds 0.5°C for at least five consecutive 3-month seasons.

A composite (a combination of a few selected events averaged into a single one) of the December-January-February SST anomalies of 20 El Niño episodes within the 1916-2016 period as defined by the above criterion is shown in Fig.(2) to illustrate the SST anomaly pattern typically associated with El Niño. We have identified the regions with statistically significant anomalies at the 5% significance level by drawing $N = 10{,}000$ random composites of size $n = 20$ from the 1916-2016 period and computing the 2.5th and 97.5th percentiles for the distribution of the SST anomalies in every gridpoint, then comparing them to our El Niño composite. The anomalous warming is centered about the equator and extends from the South American coast to the Date Line, with the maximum anomalies, which exceed 1.5°C, located in the Niño3.4 region (170°W − 120°W). Other regions outside of the tropical Pacific, which we will not focus on, also show statistically significant anomalies.

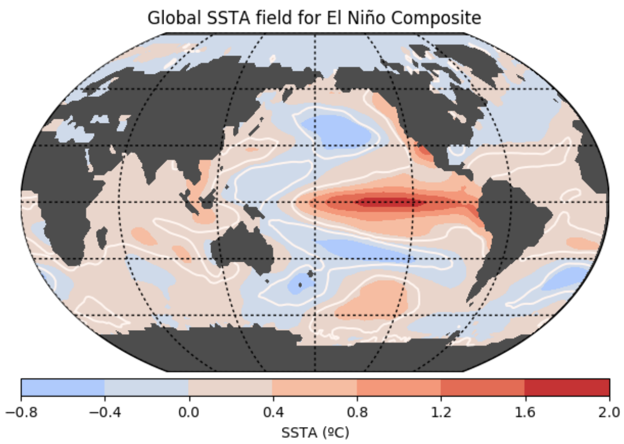

FIG. 2: Global SST anomaly composite for 20 DJF seasons corresponding to El Niño episodes in the 1916-2016 period. Within the white contours are the anomalies that are statistically significant at the 5% significance level.

ENSO episodes develop with a 3-7 year periodicity, and their evolution is tied to the seasonal cycle, typically beginning in NH spring or summer and maturing during the winter [3]. Warm events tend to last about 9 months, with exceptions of longer episodes. Despite the oscillating nature of the phenomenon, an El Niño episode may or may not be followed by a cold-phase La Niña event.

The differences observed across events in the tropical SST patterns and their evolution are a matter of great interest because changes in those modify the precipitation patterns, wind patterns and teleconnections of each event. This has contributed to the desire to characterize and sometimes classify ENSO events according to their distinctive SST patterns, as discussed next.

III. THE DIFFERENT FLAVORS OF EL NIÑO

Climate scientists have been well aware of the existence of notable differences between observed ENSO events for decades. As early as 1981, Rasmusson and Carpenter stated that their six observed episodes showed "a wide spectrum of amplitudes, as well as variations in character and timing" [3]. Trenberth and Stepaniak first coined the term "flavor" as a way to refer to the distinct SST pattern, evolution and intensity of each ENSO event, arguing that they could not be properly described by one sole index (e.g., Niño3 or Niño3.4) [4]. In particular, they found that in some events the anomalies appeared first along the South American coast and then spread to the Pacific cold tongue, whereas other events developed first in the Central Pacific and then spread eastward. Thus, they proposed a new index accounting for the differences between the anomalies in the Niño1+2 and Niño4 regions, called Trans-Niño Index (TNI), intended to be used in conjunction with Niño3.4 to give a more complete characterization of the individuality of each event. The TNI, however, was not intended to be used to separate events into categories. It was not until recently, when the sample of observed events became larger, that classifications could make statistical sense.

Although Trenberth and Stepaniak spoke of the unique character of individual events, their article served as the basis for the now prevalent distinction between two types of warm-phase ENSO events: the Equatorial Pacific (EP) El Niño and the Central Pacific (CP) El Niño. These two types differ in their spatial SST pattern as well as their evolution and, consequently, their teleconnections.

The EP El Niño, sometimes called "canonical" El Niño, is characterized by SST anomalies that are mostly located in the Niño3 and Niño1+2 areas, with the maximum anomalies in the region of the Pacific cold tongue near the Peruvian coast. The CP El Niño, in contrast, displays a pattern of SST anomalies mostly covering the Niño3.4 and Niño4 regions, with the maximum located near the Date Line. A climate shift is believed to have ocurred in the Pacific circulation around 1976-77, leading to a deepening of the thermocline in the eastern tropical Pacific, which is thought to be the reason behind a greater prevalence of events with a CP-like pattern in the past few decades [3, 5].

Several criteria other than the aforementioned TNI have been proposed to label an El Niño episode as EP or CP. Some authors simply use the Niño3 and Niño4 indices, whereas others define new indices based on mathematical analysis. The lists of EP and CP years yielded by the application of different criteria are often inconsistent, as evidenced by Yu and Kim's analysis [6]. Garfinkel et al. [7] found subtle differences in the extratropical teleconnections of the EP and CP El Niño, but they also found that those were highly dependent on the definition chosen for the CP events.

The nature of the different ENSO flavors and their generation mechanisms is not well understood, and their very existence is still a matter of debate. While authors such as Johnson [8] or Takahashi et al. [9] interpret ENSO as a continuum with a finite number of statistically distinguishable spatial patterns rather than a bimodal phenomenom, others such as Ashok et al. [10] claim that CP events are actually driven by a different mechanism than conventional ENSO events, and thus name them El Niño Modoki, "modoki" being a Japanese term for "similar, but different". Yu and Kim propose that EP and CP types can sometimes coexist during the same year, resulting in what they label a Mixed event [6].

Proponents of the ENSO continuum paradigm argue that the very strong events of 1972-73, 1982-83 and 1997-98, all of which are classified as EP by most accounts, may have caused an eastward bias in the spatial patterns of EP composites, resulting in an over-emphasis of the differences between both flavors.

IV. ARE EP AND CP EVENTS STATISTICALLY DISTINGUISHABLE? EXAMINATION FOR ONE CRITERION

The lack of consensus over the existence of different flavors of El Niño and of a uniform criterion for their classification sparks the question of whether the differences in the anomaly patterns of differently labeled episodes are statistically significant or not. To test this, we use a Monte Carlo re-sampling with replacement method to obtain the probability distribution functions of EP and CP events and compare them to evaluate the likelihood that both kinds of events can be drawn from the same statistical distribution.

Our criterion of choice to classify our episodes as either EP or CP is the El Niño Modoki Index (EMI) described in [10], because it yields a sufficient number of both EP and CP episodes (10 of each) to ensure some degree of reliability in our Monte Carlo simulated population distributions.

The EMI is defined as follows:

$$EMI = [SSTA]_A - 0.5[SSTA]_B - 0.5[SSTA]_C$$

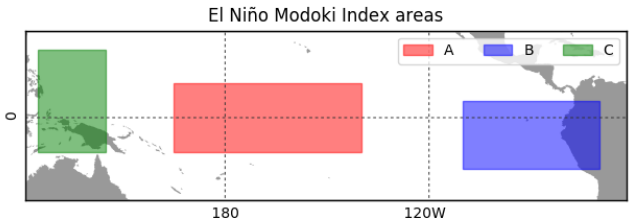

FIG. 3: Map of the three area boxes used in the computation of the EMI.

Where $[SSTA]_i$ is the area-averaged SST anomaly over the area box i. The area boxes, shown in Fig.(3), are:
A: $(165^oE - 140^oW, 10^oS - 10^oN)$
B: $(110^oW - 70^oW, 15^oS - 5^oN)$
C: $(125^oE - 145^oE, 10^oS - 20^oN)$

An event is classified as CP if its DJF EMI exceeds a threshold value of 0.7 times the seasonal standard deviation of the EMI, and EP otherwise. Composites of SSTA for both types of events obtained are shown in Fig.(4). We can see that both patterns are consistent with those described in section III.

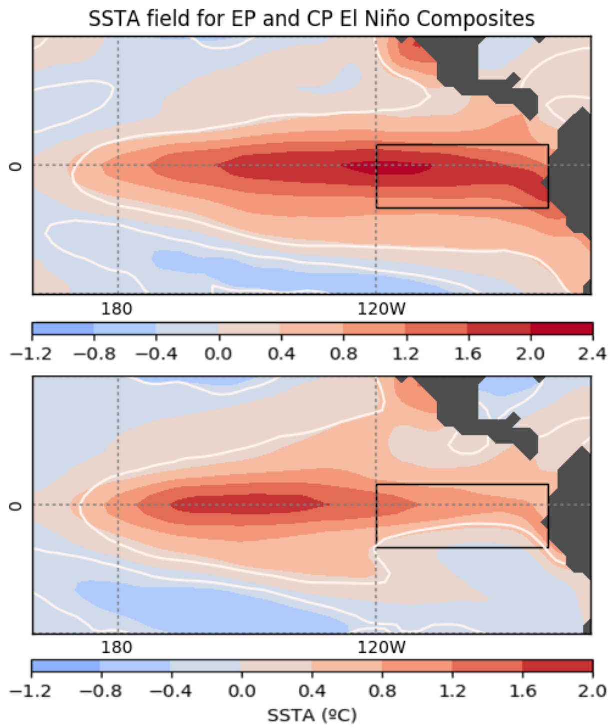

FIG. 4: SST anomaly composites (DJF) for 10 EP (top) and 10 CP (bottom) El Niño episodes in the 1916-2016 period, classified according to the EMI method. Within the white contours are the anomalies that are statistically significant at the 5% significance level. Area box "D" is shown in black.

Based on the differences between the two patterns, we have chosen to evaluate the significance of the difference in the region spanning $(120^oW - 80^oW, 10^oS - 5^oN)$.

For future reference, we label this area as "D" region.

The monthly SST anomalies in the D region are computed as the departure from the 1981-2010 climatological mean, and the linear trend is removed by subtracting a linear least-squares fit so that the analysis is focused on the fluctuations of the data about the trend.

We wish to test the hypothesis that these area-averaged anomalies are drawn from the same distribution. Because there is data for only a few events, we use a Monte Carlo re-sampling with replacement method (specifically, the bootstrap procedure) to obtain simulated population distributions of the area-averaged anomalies for EP and CP events and treat them as an estimate for the distributions from which the samples are drawn. This is done by drawing $N = 10{,}000$ samples from the original EP and CP samples, of the original sample size $n = 10$, randomly and with replacement, computing the test statistic for each of them, and building a histogram.

Drawing the samples with replacement allows for each event to be present up to n times within a given sample, or not be present at all. This method allows us to simulate many possible values of our statistic of interest and their relative frequencies and draw conclusions from them, assuming that our observed samples are representative of their entire populations. This provides us with a more accurate estimate for the population mean and confidence intervals than the initial samples alone, and no assumptions need to be made for the shape of the distributions [11].

The empirical population distributions for the EP and CP samples are shown in Fig.(5).

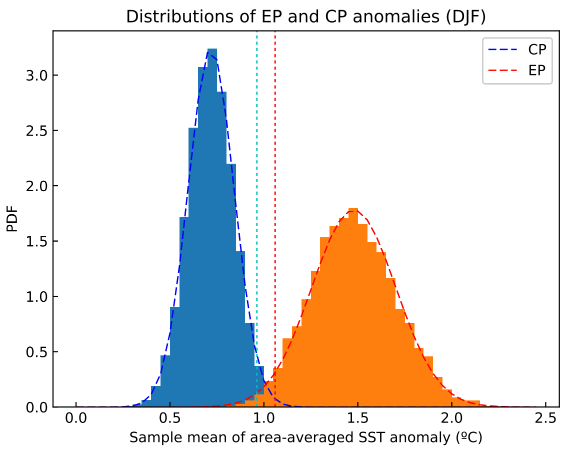

FIG. 5: Empirical population distributions of D region SST anomalies for EP and CP type events resulting from $N = 10{,}000$ bootstrap samples for each. Blue and red dotted lines represent the 97.5th percentile for the CP distribution and 2.5th percentile for the EP distribution, respectively.

As can be seen in Fig.(5), there is little overlap between the two distributions. More specifically, we can reject the null hypothesis that both samples can be drawn for the same distribution and accept our alternative hypothesis that their population distributions are different with a 95% confidence level. Therefore, we can state that the differences found in the D region are statistically significant at this level: the chance that the null hypothesis has been falsely rejected is less than 5%. Thus, it is unlikely that the differences between the two patterns are a matter of chance.

V. BRIEF ANALYSIS OF THE 2015-16 EL NIÑO EPISODE

The 2015-16 El Niño episode is regarded as one of the most extreme warm ENSO events observed since 1950, with a peak ONI of 2.6°C. Fig.(6) shows the SST anomaly field in the DJF season of 2015-16. It can be seen that there were strong anomalies exceeding 2°C over the Niño3 and Niño4 regions, and milder positive anomalies over the Niño1+2 region as well.

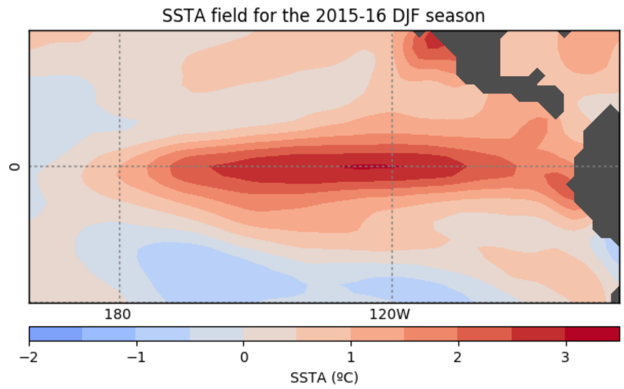

FIG. 6: SST anomaly field in the equatorial Pacific for the 2015-16 El Niño averaged over the DJF season.

The SST pattern of this episode has been said to exhibit characteristics typical of both EP and CP flavors [12]. Our own analysis based on the detrended data from the NOAA ERSST V4 dataset reveals that the area-averaged SST anomalies over the Niño3 region are greater than those over the Niño4 region, and the value of the EMI is 0.20°C, lower than $0.7\sigma = 0.36$°C. Both of these traits would be expected of an EP El Niño. The value of the D region anomaly is 1.81°C, which would fall within the EP distribution of Fig.(5), and outside of the region of overlap. There are aspects of the pattern which bear some resemblance with the CP composite in Fig.(4), such as the westward extension of the maximum anomaly region and the colder SST values in the southern Peruvian coast, but it is most consistent with what would be expected of an EP event.

The pattern for the previous June-July-August (JJA) season (not shown) also shares some traits with both the EP and CP JJA composites, with the maximum anomalies located near the Niño3 region like in the EP El Niño, but a lack of positive SST anomalies along the South American coast.

VI. CONCLUSIONS

In this work we have examined the general traits of the spatial pattern of sea surface temperature anomalies present in the equatorial Pacific during the warm phase of the ENSO cycle. This pattern shows important differences across events that have been the object of extensive study during the past few decades.

We have seen that some authors consider these differences to be indicative of the existence of different types of El Niño, with the most prevalent division corresponding to the Equatorial Pacific and Central Pacific types. Several criteria have been proposed to distinguish between these two types. Others consider ENSO a continuum where each event is unique and has distinctive characteristics.

Our Monte Carlo-based analysis revealed that, for the particular criterion proposed by Ashok et al., the EP and CP composites show statistically significant differences in their spatial SST patterns. However, several factors must be taken into account. For one, our relatively small sample sizes hinder the accuracy of the bootstrap procedure, and the chance of falsely rejecting the null hypothesis is not to be dismissed. Additionally, the existence of significant differences between both distributions is not necessarily indicative of a difference in physical mechanisms, and may simply be the result of an ad-hoc selection of events.

In the same line of thought we must keep in mind that, as evidenced by Yu and Kim in [6], the use of different criteria often assigns different labels to particular events. This, along with the analysis of the most recent El Niño episode, suggests that there may not be two clear-cut types of ENSO events, but a continuum of possibilities instead. To be able to draw conclusions, a robust definition for ENSO flavors and a larger observational sample would be needed.

Nevertheless, we have shown that the differences in the spatial SST patterns of certain events are significant, which means that the existence of well-differentiated flavors of El Niño is a possibility. The study of the SST patterns and their associated development is likely an important tool in the correct prediction of the impacts of ENSO and our understanding of the phenomenon.

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[1] R. García and E. Hernández, eds., *El Niño: climatología, efectos y predicción*, ch. 1.: "Descripción general del fenómeno ENSO", pp. 1–20. Fundación MAPFRE, 2000.

[2] K. Trenberth and National Center for Atmospheric Research Staff, eds., "The climate data guide: Nino sst indices (nino 1+2, 3, 3.4, 4; oni and tni).." `https://climatedataguide.ucar.edu/climate-data/nino-sst-indices-nino-12-3-34-4-oni-and-tni`. Accessed: December 2017.

[3] E. M. Rasmusson and T. H. Carpenter, "Variations in tropical sea surface temperature and surface wind fields associated with the southern oscillation/el niño," *Monthly Weather Review*, vol. 110, no. 5, pp. 354–384, 1982.

[4] K. E. Trenberth and D. P. Stepaniak, "Indices of el niño evolution," *Journal of Climate*, vol. 14, no. 8, pp. 1697–1701, 2001.

[5] C. Wang, C. Deser, J.-Y. Yu, P. Dinezio, and A. Clement, "El niño and southern oscillation (enso): A review," in *Coral Reefs of the Eastern Tropical Pacific: Persistence and Loss in a Dynamic Environment*, vol. 8, pp. 85–106, Springer Science Publisher, January 2017.

[6] J.-Y. Yu and S. T. Kim, "Identifying the types of major el niño events since 1870," *International Journal of Climatology*, vol. 33, no. 8, pp. 2105–2112, 2013.

[7] C. I. Garfinkel, M. M. Hurwitz, D. W. Waugh, and A. H. Butler, "Are the teleconnections of central pacific and eastern pacific el niño distinct in boreal wintertime?," *Climate Dynamics*, vol. 41, pp. 1835–1852, Oct 2013.

[8] N. C. Johnson, "How many enso flavors can we distinguish?," *Journal of Climate*, vol. 26, no. 13, pp. 4816–4827, 2013.

[9] K. Takahashi, A. Montecinos, K. Goubanova, and B. Dewitte, "Enso regimes: Reinterpreting the canonical and modoki el niño," *Geophysical Research Letters*, vol. 38, no. 10, 2011. L10704.

[10] K. Ashok, S. K. Behera, S. A. Rao, H. Weng, and T. Yamagata, "El niño modoki and its possible teleconnection," *Journal of Geophysical Research: Oceans*, vol. 112, no. C11, 2007. C11007.

[11] D. S. Wilks, *Statistical Methods in the Atmospheric Sciences.* Oxford; Waltham, MA: Academic Press, 3rd ed., 2011.

[12] L. Liu, G. Yang, X. Zhao, L. Feng, G. Han, Y. Wu, and W. Yu, "Why was the indian ocean dipole weak in the context of the extreme el niño in 2015?," *Journal of Climate*, vol. 30, no. 12, pp. 4755–4761, 2017.