Diagnostics of the La Niña events in 1900–2018

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Abstract. Diagnostics of La-Nina events from 1900 to 2018 is done in this paper using COBE SST2 data sets. Two La Niña space-time types were selected on the basis of two methods. The first of them is empirical orthogonal functions method. The second one is hierarchical cluster analysis. Both of methods showed the absolute identity two selected types. Analyzing the spatiotemporal series of the sea surface temperature anomalies (SSTA) in the equatorial Pacific two main EOFs were obtained. The first EOF mode describes ~46% of the total dispersion SST variability in the equatorial Pacific and demonstrated two consecutive La Niña events that arise after the strong canonical El Niño. The second mode accounts for ~ 21% of the total dispersion SST variability and shows a nature of the East Pacific La Niña occurrence.

1. Introduction
One of the main climate signals in the ocean-atmosphere system, which affects the state of the environment, is the El Niño – Southern Oscillation (ENSO) [1, 2]. ENSO includes two phases: warm (El Niño events) and cold (La Niña events). This article is focused on the La Niña events.

La Niña is characterized by increasing trade winds, a subsequent growth of the South Oscillation Index (SOI) and an extreme decrease of sea surface temperatures (SST) in the equatorial Pacific with a typical scale of variability from two to seven years [3]. The La Niña in comparison with the El Niño demonstrates a significant difference, both in their spatial structure and in their duration.

Most of El Niño events quickly disappear at the end of spring after the maximum positive SST anomalies (SSTA) formation in winter of the «+1» year, while many La Niña can survive next year and re-mature during the winter of the «+2» year [4, 5]. Nonlinear processes in the atmosphere are crucial for this asymmetry: large positive SSTA can cause deep convection over the cold tongue, while negative SSTA do not further affect normal dry conditions [6].

One of the important points in studying of the La Niña is a necessity to classify these events. At present, the scientific consensus about the existence of two El Niño types has been formed. As a rule El Niño events are divided into the canonical type (East Pacific) and Modoki (Central Pacific), depending on the maximum positive SST location relative to the equatorial Pacific [7–10]. At the same time, the question of the possibility to divide La Niña events into two types is still remained open.

In papers [8, 11, 12] it was said that it is difficult to distinguish two types of La Niña based on existing indices (Nino3 and Nino4), because the events of the Central Pacific type (CP) can be considered as non-linear manifestations of the East Pacific type (EP) [13].

In contrast, other studies have suggested that the existence of two types of La Niña is possible [14, 15]. For example, the CP La Niña events can be distinguished from the EP La Niña events in surface ocean currents by analyzing satellite data [15]. The authors of [16], who studied the features of
different La Niña and El Niño events according to the SST and sea surface salinity data sets also identified two types of La Niña, but did not support this result by statistical reliability due to short data series. In the recent studies [17–19] time series are used not more than 60 years old. In the works [20, 21] the authors classified the La Niña events by the hierarchical method of cluster analysis and also received two types of La Niña over a hundred years. However, this classification has some disadvantages. Firstly, this typification does not reflect the place of negative SSTA occurrence, its movement relative to the equatorial Pacific and its time existence. Secondly, this classification does not demonstrate the patterns of occurrence of different La Niña types with respect to different El Niño types.

The goal of this article is to study the patterns of the La Niña formation for more than a century-long historical period, from 1900 to 2018.

2. Data and methods

Monthly SST data sets (1850–2018) from Japan Meteorological Agency (COBE SST2) [22] with 2.5° longitude/latitude resolution are used in this study to analyze La Niña events. The cross-correlation analysis and analysis of root-mean-square deviations (RMSE) was conducted to verify the quality of SST reconstruction in COBE SST2 with monthly SST data (1981–2018) from TOGA-TAO buoys (Tropical Ocean-Global Atmosphere and Tropical Atmosphere Ocean projects) [23, 24], monthly satellite SST data (2001–2018) from MODIS (Terra Global Level 3) with 9 km spatial resolution and monthly SST data (1982–2018) from NOAA IO SST v2 with 1° spatial resolution [25]. According to the verification results, the correlation coefficient (r) of the Nino3.4 indexes (average monthly SST in the 5°N–5°S, 170°W–120°W region) is 0.99, RMSE is 0.27°C (for COBE SST2 & NOAA IO SST v2); r = 0.98, RMSE = 0.34 (for COBE SST2 & MODIS); r = 0.96, RMSE = 0.37 (for COBE SST2 & TOGA-TAO). The high values of the correlation coefficients and low RMSE values of the SST by COBE SST2 in comparison with the real SST (by buoy data and satellite observations) in the region of the definition ENSO (Nino3.4) are showed that the reconstruction was performed well in COBE SST2, that gives the basis for further La Nina analysis.

Seasonal variability and linear trend were excluded from the COBE SST2. To select the La Niña events, the optimal criterion was chosen according to the work [20], in which the threshold value of the SSTA is -0.5°C, and the minimum duration of the SSTA (D) is 5 months:

\[\text{SSTA Nino3.4} \leq -0.5°C\]
\[D \geq 5 \text{ month}.\]  

(1)

SST data for the La Niña analysis is taken since 1900, although the SST values by COBE SST2 can be taken from 1850. However, since 1900 the number of selected La Niña can be verified, for example, with a list from the Australian Bureau of Meteorology, and since 1950 the La Nina list is available on the official website of the National Oceanic and Atmospheric Administration (NOAA, USA).

The study of the laws of the La Nina formation was carried out by decomposing the spatiotemporal SSTA fields in the equatorial Pacific into empirical orthogonal functions (EOFs). The EOF method is the decomposition of a signal or data set in terms of orthogonal basic functions that are determined from these data. It is also the same as the method of principal components, only the EOF analysis allows receiving spatiotemporal patterns. In the EOF analysis the SSTA raw are projected on an orthogonal basis. The main thing here is to correctly form a matrix (object-feature), according to which the covariance matrix of eigenvectors of centered anomalies is calculated. This subsequently provides a percentage of the dispersion contribution of each getting mode.

The object-feature matrix \( \{x_i^j\} \) was formed, where \( i=1,\ldots,N \) is the number of objects, \( j=1,\ldots,M \) is the number of features, that characterize this object. This is twenty-one time period, including 2,5 years, counted from January of the "0" year (the beginning La Niña year) through June of the "+2" year.

\( M \) is the SSTA values which are averaged by latitude (0.5°N–0.5°S) in the equatorial Pacific from 150°E to 80°W (figure 1). One time period includes 3990 SSTA. It turns out the \( x_{21}^{2121} \) matrix.
The following numerical characteristics were calculated for the data matrix: $\{\bar{x}_j\}$ is a vector of average feature values (the average SSTA for each 2.5-year La Niña time period); $\{D_j\}$ is the dispersion vector of the features value; $\text{cov}(x', x'')$ is a covariance matrix of features. Then the data were centered by subtracting the mean profile and normalized using dividing by $\sqrt{D_j}$. As a result dimensionless data arrays were obtained for which $\bar{x}_j = 0$, $D_j = 1$.

The eigenvectors $\psi_j^k$ and the eigenvalues $\lambda_j$ of the covariance matrix determine the set of empirical orthogonal functions and the contribution of the $k$-th EOF to the total dispersion:

$$\left(\frac{\lambda_j}{\sum_{k=1}^{M} \lambda_k}\right) \cdot 100\%.$$  \hfill (2)

The set of empirical orthogonal functions represents a complete orthonormal basis on which each object can be decomposed:

$$x_j = \sum_{k=1}^{M} a_k \psi_j^k,$$  \hfill (3)

where $a_k$ is the amplitude of the $k$-th EOF.

In fact the spatio-temporal diagrams or Homvoller diagrams [26] were obtained, and then these diagrams were decomposed into rows by which the matrix was formed and the EOFs were calculated.

Additionally, in this study the hierarchical cluster analysis was used to classify 2.5-year series of SSTA when one or two La Niña events were observed. The essence of this method consists in sequentially combining or dividing large clusters into small ones. The Euclidean distance was chosen as a measure of the relationship between the clusters and determined by the formula:

$$d_{ij} = \sqrt{\sum_{k=1}^{m} (x_{ik} - x_{jk})^2},$$  \hfill (4)

where $x_{ik}$ and $x_{jk}$ are the values of the $k$-th variable at the $i$-th and $j$-th distances, $m$ is the number of characteristics.

3. Results and discussions

24 La Niña events were identified and analyzed using COBE SST2 data sets according to criterion (1) from 1900 to 2018. The negative SSTA and its frequency corresponded to La Nina are highlighted by blue in the figure 2. The contribution of cold ENSO episodes into the total dispersion of SSTA is 23%. The La Niña events are asymmetric to El Niño. At the same time, it needs to note that the time of existence of both El Niño events and La Niña events can be within one year, and can also last up to two and a little more than two years, and sometimes one event occurs, followed by another.

That is why, to consider the one-year, long-lasting and sequentially arising events, the identified La Niña were distributed within 2.5 years periods from January “0” to June “+2” years, where each period includes one or two La Niña events . Thus, there were 21 periods in 1900 - 2018: 1/1903-6/1905, 1/1909-6/1911, 1/1916-6/1918, 1/1924-6/1926, 1/1933-6/1935, 1/1938-6/1940, 1/1942-6/1944, 1/1949-6/1951, 1/1954-6/1956, 1/1964-6/1966, 1/1970-6/1972, 1/1973-6/1975, 1/1975-6/1975, 1/1983-6/1985, 1/1988-6/1990, 1/1995-6/1997, 1/1998-6/2000, 1/2005-6/2007, 1/2007-6/2009, 1/2010-6/2012, 1/2016-6/2018. SST anomalies changes within these 2.5-year periods in the equatorial Pacific zone, highlighted in Fig. 1, were decomposed into EOF.
Figure 2. The SST variability by COBE SST2 is in the Nino3.4 region from 1900 to 2018. Histograms of the La Niña repeatability are marked by blue.

As a result, three main EOFs were obtained. Their total contribution into SSTA dispersion amounted up to 80% in the equatorial Pacific. Now, consider three received main modes within 21 periods of 2.5 years with 1-2 La Niña events. Figure 3 shows that the first and second modes change in antiphase, while the third one practically modulates the first EOF. This indicates that the existence of two absolutely different spatio-temporal La Niña types is possible. It needs clarify what these two first modes means in the physical sense.

Figure 3. Contribution (%) of each obtained mode is for 2.5-year periods when one or two La Niña events were observed.

The first EOF mode contributes 45.6%. Figure 4a shows that such La Niña type occurs in late spring and early summer. The mature phase of this phenomenon falls on November-January and its maximally developed negative SSTA are located in the central equatorial Pacific. Figure 4a also shows that exactly one year later the second La Niña appears with a developed maximally negative SSTA in December-February. The negative SSTA of second La Niña year is weaker than SSTA of the first La Niña year in the central equatorial Pacific. In the physical sense, the first EOF mode describes two consecutive La Niña events that arise after the strong canonical El Niño.
That is, the first mode shows that after intense El Niño La Niña arises with the most intense negative SSTA formation in the central equatorial Pacific in late autumn and early winter. After that, La Niña fades, but exactly one year later it intensifies again. This proves the concept of a two-year La Niña and confirms that El Niño and La Niña events are asymmetric to each other [4, 5].

The second EOF mode contributes 21.2% (figure 4, b). This La Nina type occurs in early spring in the east equatorial Pacific. The maximum negative SSTA are developed in June-August. The La Niña event ends in winter of «+1» year in the central equatorial Pacific. La Niña with the spatiotemporal structure of the second EOF mode is purely East Pacific type described in works [20, 21]. Such events occur in the eastern equatorial part of the Pacific, develop there and exist not more than one year. It is assumed that the formation of El Niño «Modoki» is possible after such La Niña events.

Figure 4. Spatiotemporal diagrams of the obtained modes: the first EOF (a), the second EOF (b).

At the same time, 2.5-year series of SSTA changes in the equatorial Pacific were classified using hierarchical cluster analysis (figure 5). As a result, it was found that the La Niña periods with the largest contribution of the second mode were assigned to the first cluster, and the La Niña periods with the largest contribution of the first mode were combined into a second cluster.

Figure 5. The dendogram of hierarchical cluster analysis of 2.5-year SSTA periods (La Niña years) in the equatorial Pacific is calculated by COBE SST2 from 1900 to 2018. The linkage distance is Euclidean distance
4. Conclusions
Two spatial-temporal La Niña types were obtained and patterns of their formation are described from 1900 to 2018 by decomposing the longitude-time SSTA diagrams into empirical orthogonal functions and applying hierarchical cluster analysis.

The results of EOF decompositions showed that the first mode contributes ~ 46% to the total SSTA variability in the equatorial Pacific. In the physical sense this EOF mode demonstrates two consecutive La Niña events arisen after the strong canonical El Niño. In general after intense El Niño the most negative SSTA is formed in the central equatorial Pacific Ocean in late autumn and early winter, then faded and intensified again exactly one year later. This proves the concept of the two-year La Niña existence and confirms that El Niño and La Niña events are asymmetric to each other.

The second EOF mode accounts for ~ 21% of the total SSTA dispersion variability. La Niña events of this type are only Eastern Pacific character. Such events occur in the eastern equatorial part of the Pacific, develop there and exist for no more than a year. After this La Nina event probably the El Nino «Modoki» can be formed, but not always.

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