Links between interannual variations of sea level in the Equatorial Pacific and climate indices

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Abstract

A 27-year record of altimetry sea level height observations data and climate indices are used to study climatic interannual variation in the equatorial Pacific. Performing an Empirical Orthogonal Function (EOF) analysis and correlation analysis between principal components and climate indices, we find the leading mode exhibits a strong El Niño pattern, in which the principal component significantly correlates the ENSO index on interannual scale and PDO index on decadal scale.

1 Introduction

The equatorial Pacific region (29.75°S-29.75°N and 100°E-280°E) is characterized by strong interannual variability of sea level[1]. Abnormal conditions can lead to an increased risk of flooding of low-lying coastal areas in the region and have huge impacts on global weather, climate, agriculture and economy. Understanding the driving mechanism behind these variations is crucial. If we can find a connection between climate indices and the sea level variations, we can use climate and weather modelling to model and predict annual sea level change. In this report, we investigate the connection between interannual sea level variability in the equatorial Pacific and the climate indices using EOF method and correlation analysis.

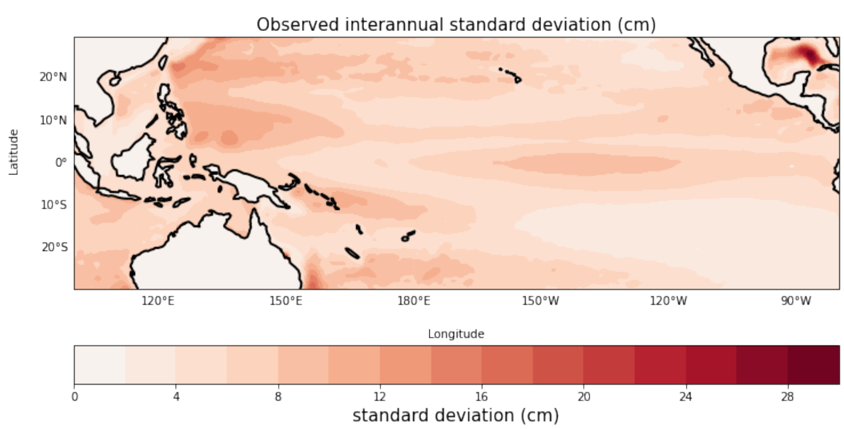


Figure 1: Standard deviation in observed interannual sea level variations

As figure 1 shows, significant interannual variations are located in the northwest, southwest, and east-central equatorial Pacific, where the observed interannual standard deviation exceeds 16 cm, and it is considered to associate with climate variability, such as El Niño–Southern Oscillation (ENSO)[1].

2 Data

2.1 Sea level height anomalies

A 27-year record of monthly sea surface height anomalies (SLA) were obtained from the Copernicus Marine Service[2], ranging from April 1993 to May 2020. Because we are interested in interannual variability, the long-term trend and the seasonal cycle have been have been removed. The SLA is a merged gridded (L4) product, estimated by Optimal Interpolation, merging the measurement from the different altimetry satellites (Jason-3, Sentinel-3A, HY-2A, Saral/AltiKa, Cryosat-2, Jason-2, Jason-1, T/P, ENVISAT, GFO, ERS1/2). The satellites measure sea level heights by sending out EM-waves and measuring the reflection time from the water surface. A description of the processing chain can be found at the website of CNES/CLS[3]. To reduce the data size, the data is regridded from original 0.25x0.25 degrees to a spatial resolution of 0.5x0.5 degrees, covering the area between 29.75°S-29.75°N and 100°E-280°E. The netCDF file has three coordinates: longitude, latitude and time. Longitude and latitude have unit of degrees and the time has a decimal representation in unit of years. Figure 2 shows a visualization of the data in December 1997.

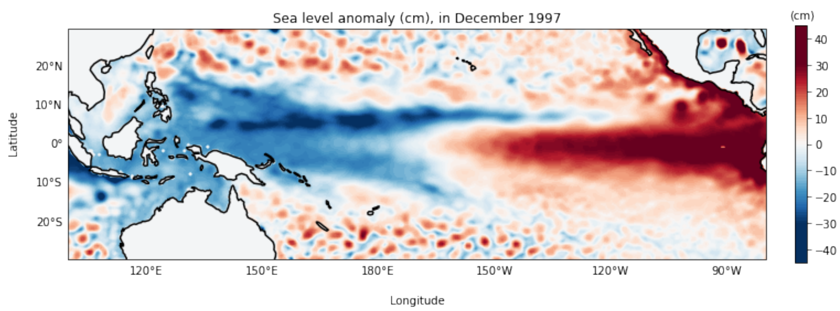


Figure 2: Sea level anomaly in December 1997.

2.2 Climate indices

Monthly ENSO data set was downloaded from NOAA[4] running from January 1870 to December 2020 and a monthly PDO index data set from KNMI/NOAA[5] running from January 1899 to December 2020. Both these data sets consist of 13 columns in a text file. The first column is the year of the data and the other 12 columns are the monthly data in those years running from January to December. To use these data sets as one continuous array, we both need a time axis in steps of months and flatten the data.

The ENSO index is the surface temperature anomalies in region Niño 3.4 of the equatorial pacific. The ENSO index is calculated from the HadISST1. It is the area averaged SST from 5S-5°N and 170-120°W, which is relative to average global surface temperature anomalies, to remove a global trend. A showing of the region and the values in the data set can be seen in figure 3.

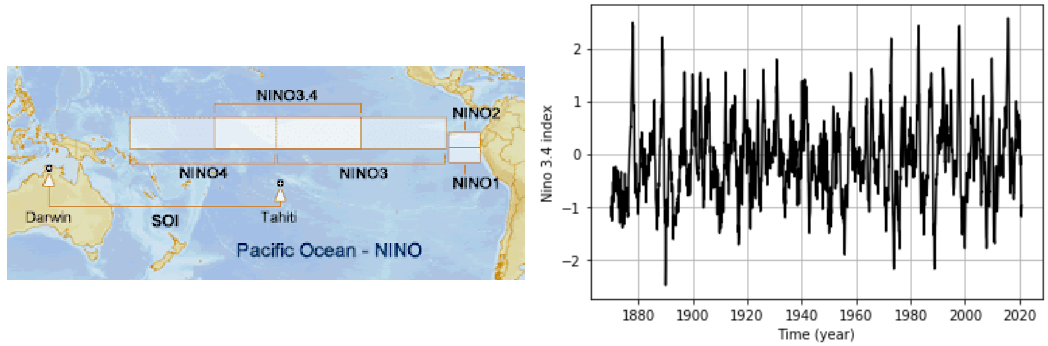


Figure 3: **a.** Region of ENSO indicated on a map of the equatorial Pacific.[6] **b.** The data set of the ENSO index from NOAA spanning from January 1870 to December 2020.

The PDO index, or Pacific Decadal Oscillation, is the principle component of the first empirical orthogonal function (for EOF see also section on Methods) corresponding to the sea surface temperature anomalies in the Pacific Ocean north of 20°N. This is relative to average global surface temperature anomalies, to remove a global trend. The region and corresponding data set can seen in figure 4.

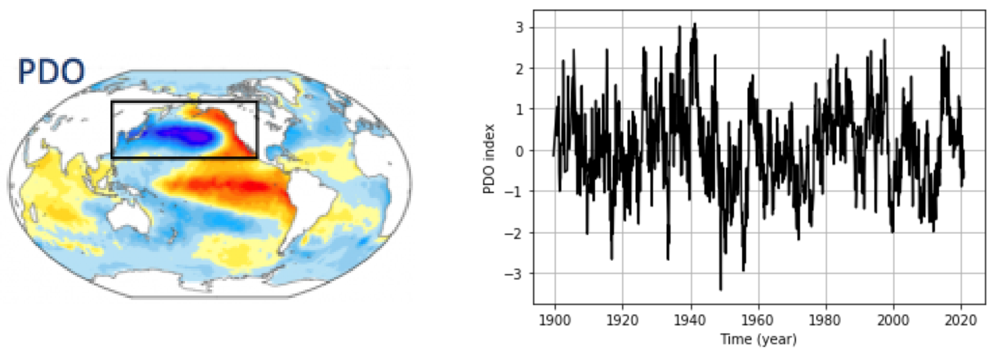


Figure 4: **a.** Region of PDO indicated on a map of the Pacific.[7] **b.** The data set of the PDO index from NOAA spanning from January 1899 to December 2020.

3 Methods

3.1 EOF analysis

Empirical orthogonal function (EOF) analysis is used to identify the dominating spatial patterns of SLA interannual variability. One projects the satellite observation data on an orthogonal basis derived from the eigenvectors of its covariance matrix, the corresponding eigenvalues measure the percentage of variance explained by each pattern[8]. We associate SLA and climate variability by comparing the dominant EOF patterns with corresponding principal component time series. Here, we briefly review the steps we conducted in the report:

1. Reshape the data matrix. Convert the 3-Dimensional matrix to a 2-Dimensional matrix with the rows corresponding to the time and the columns to the position.

2. Compute the covariance matrix. Work with the transpose of the matrix to avoid memory problems when computing the covariance matrix, then remove the mean from the entire dataset, compute the covariance matrix as the product of the matrix transpose and itself.

3. Compute the eigenvalues and eigenvectors. The sum of eigenvalues should equal the total variance of the data.

4. Visualize the principal components and their associated time series.

5. Reconstruct the dataset with the leading modes. Here we define a critical value of the total variance as 70%, the the cumulative explained variance should exceed the threshold value.

3.2 Correlation analysis

To further study the driving mechanism of behind the main mode of variability, we carry out a correlation analysis between the time series of the EOF coefficients with climate indices, such as ENSO index and PDO index.

We use Pearson's correlation coefficient, R, which determines how well the two variables co-vary in time or space. This can simply be calculated using $numpy.corrcoef(x, y)$.

4 Results

The EOF 1 exhibits an El Nino pattern, the sea level anomaly in the eastern Pacific ocean shows positive anomaly while the western Pacific is negative. The leading principal component (PC1) is significantly correlated with the NINO 3.4 index (R=0.93) on interannual scale from 1993 to 2020, see figure 5.

The principal component 1 coefficient is normalized and the most significant signals in the time series are in 1997-1998 and 2015-2016 (Figure 5, B), indicating the major ENSO events, which are consistent with the truth. One can also roughly approximate the signal oscillation period to 4-5 years.

Furthermore, the principal component 1 of EOF also correlates with the PDO index on a decedal time scale (R=0.94) (Figure 5, C). To get to this result we take a running average of 120 months, or 10 years, of both the PDO index series data set and the PC1 component.

Lastly, the principal component 2 of EOF is also found to be moderately correlated with ENSO after a lag of 7 months (R=0.71). To find this result we delayed the time series of the EOF 2 coefficient with 7 months before correlating.

There are 329 eigenmodes in total and the first 323 eigenmodes explain all the variance (Figure 6). The first eigenmode explains 27.39% of total variance, the second 6.49%, and the third 4.82%. Based the a subjective truncation rule mentioned in the method, the first 60 eigenmodes explains 72.25% of total variance, which are used to reconstruct the data set.

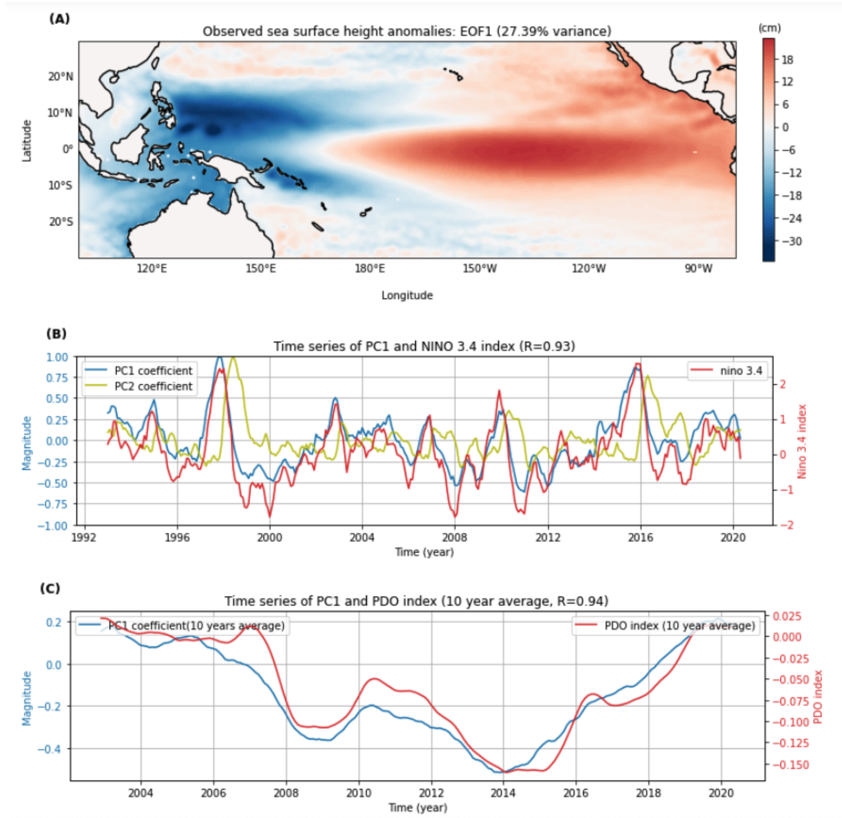


Figure 5: The first EOF pattern (A) and correlation between PC 1 and NINO3.4 index (B)

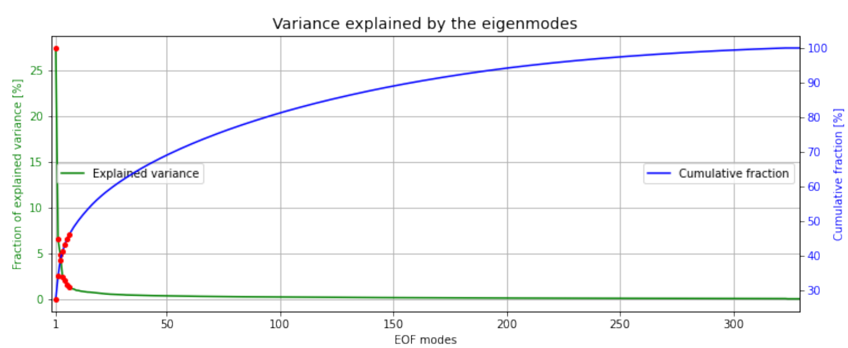
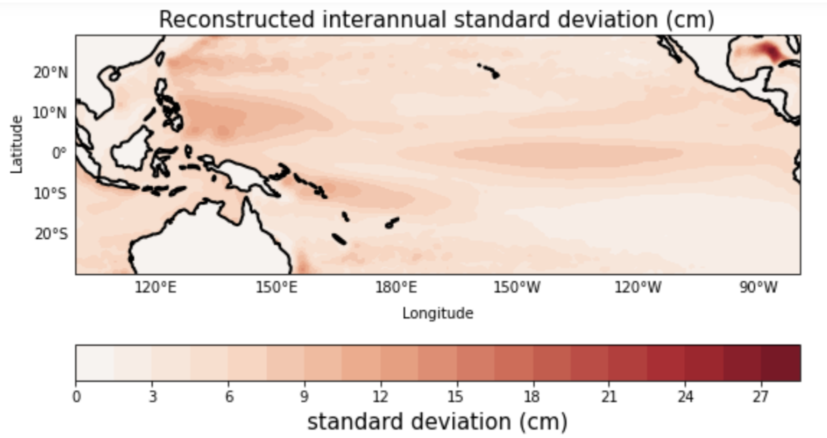


Figure 6: variance explained

The reconstructed data set represents the original date set quite well, the standard deviation is similar with the original one discussed in the introduction. One can clearly see the reconstructed date set filters out some insignificant and unwanted processes in margins of the domain (Figure 7).



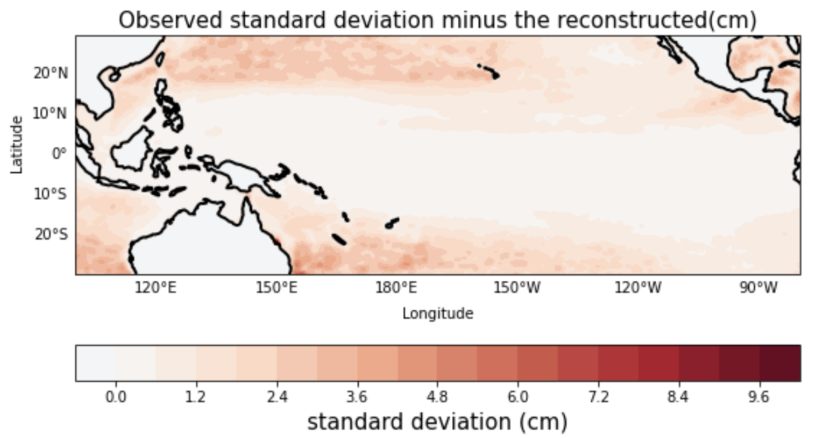


Figure 7: reconstructed standard deviation and its difference with the original one

5 Discussion and conclusions

From the pattern of the first EOF mode, we find it represents the variance in the domain in the most efficient way. Strong Kelvin waves are seen in the central and eastern Pacific ocean, and Rossby waves are located in the western Pacific. It shows that the major interannual variability of sea level anomaly occurs in the equatorial Pacific and it is associated with El Niño–Southern Oscillation (ENSO). Sea levels rise in the eastern Pacific and fall in the weatern Pacific during El Niño event.

The EOF 1 coefficient time series manifests the most significant signal in 1997-1998, which is regarded as one of the most powerful ENSO events in recorded history. A spectral analysis indicates the typical time scale of the oscillation is around 4.17 year.

The reconstructed data set filters out some insignificant processes in the north and the south of the domains, thus can represent the main pattern even better.

The PC1 is significantly correlated with the ENSO index (R=0.93) and PC2 is moderately correlated with the ENSO index after a 7 months delay (R=0.71), indicating the ENSO events play an important role in Sea level anomalies in equatorial Pacific. We also see a significant correlation between PC1 and the PDO index on decedal timescales (R=0.94), indicating a variation in sea level heights on longer timescales than interannual and maybe also indicating that the ENSO drives the PDO index on decadal scales.

During strong El Niño events, such as observed in 1997–1998, sea level drops around tropical western Pacific islands by up to 20 to 30 cm, at the same time rise in the eastern Pacific—especially along the equator, where anomalies exceeding 35 cm have been recorded around the Galápagos Islands [1]. Furthermore, it says that ENSO events can even have an effect on sea level changes more than half a year later, only in other areas. This is similar to the effect ENSO has on global temperatures, which also lags around 6 months [9]

We only investigated the sea level anomaly and NINO3.4 index, some other climate variables also play a role in the equatorial Pacific region, such as sea surface temperature. These other climate variables could explain the rest of the variance, so that could be done in future research. Future research could also make use of a bigger sea level anomaly data set, that could enhance the significance of the correlation. Then we could conclude more of a causation instead of only correlation. Besides, we only focus on the first EOF pattern, it is known that combining several leading EOFs may explain more variance. However, one should keep in mind the EOFs modes do not always represent physical processes.

References

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