NON-LINEAR SEA LEVEL VARIATIONS IN THE EASTERN TROPICAL PACIFIC

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ABSTRACT. The objective of this paper is to provide an insightful interpretation for the non-linearity of the inter-annual signal in sea level change in the eastern tropical Pacific. Such a non-linearity has been already discussed elsewhere for global ocean. Herein, the residual sea level anomaly time series from TOPEX/Poseidon and Jason-1 altimetry is obtained by removing the significant deterministic signals from the original sea level anomaly data. Since the eastern tropical Pacific is a profound region where many processes responsible for driving the El Niño/Southern Oscillation (ENSO) act, it is possible to link a few of them with the non-linearity of sea level change. In particular, not only local, usually weak, ocean-atmosphere interactions exist in the eastern equatorial Pacific but this region is also remotely impacted by climatic processes acting in the western equatorial Pacific where the ocean-atmosphere coupling is the strongest. The detected non-linearity of sea level change is due to the asymmetry between warm and cold ENSO episodes. Such an asymmetry can be driven by the non-linear dynamical heating associated with strong ENSO events.

Keywords: El Niño/Southern Oscillation (ENSO), dynamical heating, non-linear time series, satellite altimetry, TOPEX/Poseidon, Jason-1

1. INTRODUCTION

The eastern tropical Pacific's environment is particularly vulnerable to the El Niño/Southern Oscillation (ENSO). It concerns many environmental variables, e.g. sea surface temperature fluctuations, sea level change and atmospheric pressure variability. The irregular changes in the velocity of the tropical easterly winds remain the main factors controlling El Niño and La Niña events (e.g. Philander, 1990; Clarke, 2008). Much of ENSO non-linearity is driven by the regime of these winds and hence many aforementioned variables may inherit departures from linearity.

ENSO is said to be non-linear as the warm phase (El Niño) and the cold phase (La Niña) reveal dissimilar magnitudes. It has been quantitatively evaluated by An and Jin (2004) who linked ENSO non-linearity with the warm-cold asymmetry and the non-linear dynamical heating (Jin et al., 2003). The asymmetry in question has also been detected by Hunt and Elliot (2003) who argued that a stochastic process may control much of such a non-linearity. Earlier, Hoerling et al. (1997) found the physical basis behind the non-linearity of the analysed system and confirmed the indirect relation between warm and cold ENSO episodes.

In addition, some researchers used purely statistical measures to detect ENSO non-linearity. For instance, Burgers and Stephenson (1999) as well as Niedzielski and Kosek (2010) utilised the notions of skewness and kurtosis to diagnose the intrinsic non-linear dynamics of sea surface temperature fluctuations and sea level variations, respectively. Not only higher-order statistics have been used to diagnose ENSO non-linearity. Indeed, high-degree statistical methods, such as a non-linear principal component analysis, have also been utilised (Wu and Hsieh, 2003; Hsieh, 2004; An et al., 2005).

Sea level change data can now be obtained from classical tide-gauge measurements (Douglas, 2001) and satellite altimetry (Fu et al., 1994; Lafon, 2005; Cazenave et al., 2008). There is a wide range of science goals which can be attained using such data. Among others, they include long-, medium-, and short-term sea level variability analyses aiming at the investigations towards climate change and ocean-atmosphere dynamics. One of the essential issues related to the above-mentioned coupling is ENSO impact on local sea level fluctuations (e.g. Cane, 1984; Clarke, 2008). The nature of such an influence determines the intrinsic properties of sea level variation signal in a temporal domain (e.g. Niedzielski and Kosek, 2009). Non-linear interactions between oceanographic and atmospheric processes are often used for sea level change modelling (Röske, 1997). The non-linearity of sea level variation has also been reported for long-term trends, both globally and locally (Church and White, 2006; Jevrejeva et al., 2006; Cazenave et al., 2008). Such a non-linearity may indicate the existence of the meaningful acceleration in sea level variation. The non-linearity of sea level change does not only concern trends but also de-trended residuals. Indeed, it has been recently shown by Niedzielski and Kosek (2010) that the global patterns of non-linearity of sea level variation around linear trends and periodic terms are quite patchy with the strongest departure from the normal distribution located in the tropical Pacific.

Following the paper by Niedzielski and Kosek (2010), it is now known that the equatorial Pacific is a specific zone in the global ocean where the non-linearity of sea level variation is somehow linked to the heavy-tailness of the underlying probability distribution. In particular, the east section of the tropical Pacific reveals the most meaningful non-linearity. It is thus necessary to zoom into this zone in order to study and interpret the vital changes in ENSO-driven sea level variability. Indeed, sea level change in the eastern tropical Pacific is influenced by both local, probably weak (Clarke et al., 2000), ocean-atmosphere coupling as initially argued by Bjerkens (1969) as well as by remote processes acting in the western tropical Pacific where the ocean-atmosphere interaction is the strongest (e.g. Clarke, 2008). In the frame of the delayed oscillator model, the study region is said to be responsible for initiation of El Niño (e.g. Wang and Fiedler, 2006). This paper addresses the issue of a detailed analysis and interpretation of the non-linearity of sea level change in the eastern tropical Pacific. Hence, this paper complements the recent investigation by Niedzielski and Kosek (2010).

2. DATA AND METHODS

The TOPEX/Poseidon and Jason-1 sea level anomalies gridded time series, obtained from the Center for Space Research, University of Texas at Austin, USA, are processed in this paper. These data are corrected for such effects as ocean tides, inverted barometer, tropospheric delay, ionospheric delay and biases from remaining sources. For the purpose of this study, the spatial extent is limited to the eastern tropical Pacific and the Caribbean Sea and is within the rectangle 20°S–20°N, 70°–110°W. The data are limited to the following time interval: 10.01.1993–14.07.2003. The spatial resolution of TOPEX/Poseidon and Jason-1 gridded time series is 1°×1° whereas the temporal resolution is approximately equal to 10 days. The gridded time series from TOPEX/Poseidon with the identical spatial extent was processed by

Niedzielski and Kosek (2009) in order to calculate the sea level anomaly prediction during El Niño, La Niña and normal conditions. If no data are available for a specific TOPEX/Poseidon or Jason-1 cycle, the linear interpolation serves well the purpose of filling a gap in a temporal domain. The technical details on merging of TOPEX/Poseidon and Jason-1 data can be found in the paper by Niedzielski and Kosek (2010) focusing on the global patterns of ENSO non-linearity in sea level fluctuations.

Two types of sea level anomaly residuals are analysed in this paper. The first data set under consideration is the gridded residual sea level anomaly time series without the linear trend (denoted later as “A-residuals”). For each grid, A-residuals (R_t^A) are obtained using the following formula:

$$R_t^A = SLA_t - (at + b),$$

where SLA_t is the sea level anomaly time series at time t ; $(at + b)$ is the linear trend in the sea level anomaly time series for which parameters a and b are estimated using the least-squares technique. Thus, A-residuals comprise both seasonal and irregular variations in sea level change. The physical meaning of them is that they capture different types of short- and medium-term sea level variability (deterministic and stochastic) other than monotonic long-term trends.

The second data set is the gridded residual sea level anomaly time series without the following terms: linear trend, annual oscillation, semi-annual oscillation and 62-days alias-type oscillation (denoted later as “B-residuals”). For each grid, B-residuals (R_t^B) are computed using the following expression:

$$R_t^B = SLA_t - A_1 \sin(\omega_1 t + \phi_1) - A_2 \sin(\omega_2 t + \phi_2) - A_3 \sin(\omega_3 t + \phi_3) - (at + b),$$

where SLA_t is the sea level anomaly time series at time t ; $(at + b)$ is the linear trend in the sea level anomaly time series defined by parameters a and b ; $A_1 \sin(\omega_1 t + \phi_1)$, $A_2 \sin(\omega_2 t + \phi_2)$ as well as $A_3 \sin(\omega_3 t + \phi_3)$ describe annual, semi-annual and 62-days terms with amplitudes (A_1, A_2, A_3), phases (ϕ_1, ϕ_2, ϕ_3) and fixed frequencies appropriate for those oscillations ($\omega_1, \omega_2, \omega_3$) (see Niedzielski and Kosek, 2010). Amplitudes, phases and trend parameters are estimated using the least-squares method. Hence, the strongest signal in B-residuals is associated with irregular oscillations. Such irregular variations are understood as departures from a regular deterministic function describing both monotonic long-term trends as well as periodic signals. In particular, for the eastern equatorial Pacific such irregular variations are mostly controlled by ENSO episodes.

Both A-residuals and B-residuals are processed along the lines of the article by Niedzielski and Kosek (2010). The sea level variability in the eastern tropical Pacific is analysed by means of standard deviation, skewness and kurtosis. These notions are common in statistics and thus can be found elsewhere (e.g. DeCarlo, 1997; Joanes and Gill, 1998). The combination of these measures allows for evaluation of the non-linearity (Burgers and Stephenson, 1999). In addition, the statistical significance of departures from 0 (skewness) and 3 (kurtosis), the intrinsic values for the normal distribution, are assessed by D’Agostino and Anscombe-Glynn tests, respectively (D’Agostino, 1970; Anscombe and Glynn, 1983).

3. RESULTS AND DISCUSSION

The standard deviation of A-residuals ranges from 2.1 cm to 10.3 cm. The lowest values correspond to the region located south of 10°S parallel, north of 15°N and to the Caribbean Sea. The highest values are observed near the west coast of Columbia and Panama as well as in the vicinity of the Equator for longitudes greater than 100°W. Two parallel zones with the considerably high values of standard deviation around a linear trend are clearly seen along the Equator and around 10°N parallel (Fig. 1a). The Intertropical Convergence Zone (ITCZ), usually between 5°N and 10°N in the study area, tends to move northward and southward revealing both seasonal and inter-annual fluctuations (e.g. Clarke, 2008). Knowing that the seasonal and inter-annual sea level variability is included in A-residuals it can be hypothesized that the considerable standard deviation at 10°N can be caused by the ITCZ migration. The zone from the ITCZ to the Mexican coastline can be linked to the eastern Pacific warm pool (water temperature higher than 28.5°C and being a part of the Western Hemisphere warm pool) which also reveals both the seasonal and inter-annual variability (Wang and Fiedler, 2006) justifying the higher standard deviation values.

Fig. 1. Standard deviation of sea level anomaly residuals: A-residuals (A) and B-residuals (B). Land grids are depicted in medium grey and no data or poor interpolation grids are plotted in dark grey.

In contrast, the zone related to the ITCZ cannot be clearly distinguished for the corresponding analysis of B-residuals (Fig. 1b). This is probably because of a removal of annual and semi-annual seasonal cycles in the process of deriving B-residuals. Indeed, the overall comparison between Figs. 1a and 1b shows the significant reduction of the standard deviation for latitudes around 10°N. Thus, it is likely that the highest standard deviation of A-residuals discussed above is mainly caused by the seasonal ITCZ migration. The most considerable standard deviations of sea level anomaly of B-residuals persist at the Equator and along the western coastline of Middle America (with possible extension towards the eastern Pacific warm pool) and thus much of the sea level change variability in these regions can be explained by the irregular inter-annual variations, possibly of stochastic nature. According to many researchers (e.g., Nerem et al., 1999; Wang and Fiedler, 2006; Niedzielski and Kosek, 2010) the interpretation can be sought amongst ENSO-related investigations.

One possible explanation can be linked to the thermosteric effect associated with the 1997/1998 El Niño, which was earlier found to be responsible for local sea level rise in the

studied region (Cazenave et al., 2003). A recent study by Antonov et al. (2005) confirmed that the thermosteric sea level change in the entire equatorial Pacific (15°S-15°N) reveals ENSO-driven inter-annual variability. More locally, high sea surface temperatures are recorded during warm ENSO episodes in the eastern Pacific warm pool (Fig. 17; Wang and Fiedler, 2006) what can explain the high standard deviation of B-residuals in this region. Hence, such an occasional and local thermosteric impact due to ENSO episodes may contribute to the rise of uncertainty in sea level change and thus justify the considerable standard deviation. It is also possible that the high standard deviation around the Equator is associated with the zonal displacement of the eastern edge of the western Pacific warm pool which, in case of strong El Niño episodes, may reach the eastern tropical Pacific or even the eastern Pacific Ocean boundary (Clarke et al., 2000). Such a displacement is due to equatorial Kelvin and Rossby waves and is controlled by the delayed negative feedback which is responsible for restoring the original position of the western Pacific warm pool. It can be hypothesized that fluctuations of a location of the western Pacific warm pool contribute to the increase in the standard deviation of sea level because of the supply (removal) of the additional warm water to (from) the eastern tropical Pacific. The equatorial Kelvin waves were earlier found to influence the sea level rise along the western coast of South America (Cane, 1984).

In addition, the reader should note that the standard deviation of both A- and B-residuals increases towards the coastline. The possible interpretation can be twofold and may comprise the issue of the higher uncertainty of altimetric measurements in coastal areas as well as the above-mentioned problem of ENSO-related forcing. Indeed, the constraints in the process of obtaining sea level heights due to noisy radar signal as well as poor geophysical corrections near the shore were reported elsewhere (Kuragano and Shibata, 1997; Andersen and Knudsen, 2000; Deng and Featherstone, 2006). On the other hand, equatorial Kelvin waves can be reflected from the eastern Pacific boundary and propagate poleward as coastal Kelvin waves (e.g. Clarke, 2008). This may provide an alternative justification for the higher standard deviation along the western coastline of North America (stronger evidence) and South America (weaker evidence). The teleconnection between ENSO and the eastern Pacific warm pool (Wang and Fiedler, 2006) can explain the higher standard deviations of sea level anomaly residuals along the coasts of North America than along the Southern American coastline. Although standard deviation is a measure of uncertainty and detects unusually high local sea level fluctuations during warm and cold ENSO episodes, it cannot be interpreted in terms of non-linearity of the system as variance is not equivalent with kurtosis (DeCarlo, 1997). Hence, the analysis of skewness and kurtosis is required.

The skewness of A-residuals varies between -0.4 and 2.3. The greatest values of skewness are again aligned along the Equator and the zone of the high skewness extends latitudinally towards the coastline (Fig. 2a). Isolines in Fig. 2 depict p -values (0.01, 0.05, 0.1) of the D'Agostino test which allows one to assess the statistical significance of skewness departures from zero. This confirms that the zone of the statistically meaningful skewness of A-residuals in the eastern tropical Pacific is aligned along the Equator and the western coastline of North and South America (Fig. 2a). These regions are characterised by the right-skewness of the empirical probability law of sea level anomaly and thus by a departure from the normal distribution. Some areas located outside 10°S-5°N latitudes, including the Caribbean Sea, reveal the lower skewness, locally suggesting insignificant departures from zero (Fig. 2a). In particular, note that the skewness of A-residuals for the ITCZ or the eastern Pacific warm pool does not meaningfully depart from zero.

A slightly different picture is provided by Fig. 2b which shows the results of the similar exercise for B-residuals. In what follows, the zone of relatively high values of skewness extends to the region limited by latitudes 15°S-10°N with the tendency of further latitudinal

extension in the vicinity of the western coast of South America. Both the ITCZ and the eastern Pacific warm pool are characterized by a distinct zone of the high skewness of B-residuals extending from Middle America towards southwest. In accordance with the results of the D'Agostino test, only the Caribbean Sea and the northwestern and southwestern sections of the study area are the regions where the skewness values remain around zero. The zone of the greatest values of the sea level anomaly skewness explained by distributions other than the normal one is noticed slightly south of the Equator and extends towards South America. The comparison between Figs. 2a and 2b clearly indicates that almost solely irregular inter-annual changes in B-residuals of sea level anomaly are more skewed to the right than A-residuals.

Fig. 2. Skewness of sea level anomaly residuals: A-residuals (A) and B-residuals (B). Contour lines indicate specific p -values (0.01, 0.05, 0.1) of the D'Agostino test. Land grids are depicted in medium grey and no data or poor interpolation grids are plotted in dark grey.

The kurtosis of A-residuals is the highest, ranging from 7 to 9, in the vicinity of the Equator with the latitudinally wide zone near the South and Middle America (in the vicinity of the eastern Pacific warm pool) (Fig. 3a). This finding together with the aforementioned right-skewness indicates that in this region the empirical probability density functions of sea level anomaly are more peaked than the normal distribution. The low values of kurtosis, similar to those typical for the normal distribution, prevail in the regions located outside 10°S-5°N, including the Caribbean Sea and the ITCZ. This is confirmed by isolines of p -values (0.01, 0.05, 0.1) of the Anscombe-Glynn test which detects the significant departures of kurtosis from 3. A slightly dissimilar spatial pattern can be observed for B-residuals in Fig. 3b. The kurtosis for B-residuals is generally higher and exhibits a spatially wider zone of values meaningfully departing from 3 with two local spatial maxima, i.e. near the Equator (slightly shifted southward) together with coastal areas and offshore at 5-8°N, thus including the eastern Pacific warm pool and the ITCZ.

The combined interpretation of skewness and kurtosis for the eastern tropical Pacific indicates that the most meaningful departures from the normal distribution are aligned along the Equator, in the vicinity of the ITCZ, near the eastern Pacific warm pool and in coastal areas. The fact that sea level variation in coastal areas experiences some non-Gaussian dynamics can be explained by both the uncertainty of altimetric data along the shore (Kuragano and Shibata, 1997; Andersen and Knudsen, 2000; Deng and Featherstone, 2006) as well as by ENSO impact. The non-Gaussian variability of sea level along the Equator,

along the ITCZ and in the eastern Pacific warm pool seems to be associated with the inter-annual signal controlled by ENSO.

Fig. 3. Kurtosis of sea level anomaly residuals: A-residuals (A) and B-residuals (B). Contour lines indicate specific p -values (0.01, 0.05, 0.1) of the Anscombe-Glynn test. Land grids are depicted in medium grey and no data or poor interpolation grids are plotted in dark grey.

Knowing that B-residuals comprise inter-annual terms and do not consist of annual and semi-annual components and that the eastern tropical Pacific is vulnerable to weak ocean-atmosphere coupling (Wang and Fiedler, 2006) as well as to the remote impact of processes acting in the western tropical Pacific (Clarke et al., 2000), it is possible to hypothesize a few interpretations. According to Hannachi et al. (2003), departures from the normal distribution of sea surface temperature can be linked to the non-linearity of ENSO understood as the asymmetry between warm and cold ENSO phases. Indeed, the dynamical heating, which may influence sea level change, controlling the aforementioned asymmetry is also perceived to be non-linear. According to Jin et al. (2003), the non-linear heating is considerable for strong ENSO episodes leading to the above-mentioned asymmetry and, on the other hand, is negligible for moderate ENSO events for which no asymmetry between El Niño and La Niña is noticeable. Thus, this interpretation can also hold for sea level change in the eastern equatorial Pacific where sea level variability may be influenced by eastward propagation of the western Pacific warm pool and by weak local ocean-atmosphere interactions (thus processes linked with the dynamical heating). Different aspects of ENSO non-linearity were found by Tziperman et al. (1994) who claimed that the resonance between ocean-atmosphere oscillator and the seasonal cycle was non-linear. Although it is difficult to link such a finding with a simple departure from the normal distribution discussed in this paper, the reader should note that any disruption of linearity of ENSO generating process will have a certain impact on the underlying probability law of different ENSO-sensitive time series.

4. CONCLUSIONS

The eastern tropical Pacific reveals four distinct zones of high sea level change uncertainty, namely the equatorial zone, the ITCZ, the eastern Pacific warm pool and coastal areas. High sea level variability measured by the variance can be explained by ENSO physics (near the Equator, in the vicinity of the ITCZ, in the eastern Pacific warm pool and in coastal waters) as well as by the uncertainty of altimetric observations (coastal waters). The non-linearity of sea level change in the eastern equatorial Pacific is confirmed by indicating departures from the

normal distribution, for zones near the Equator, along the ITCZ, in the eastern Pacific warm pool and in coastal areas. Such a non-linearity may be driven by the non-linear dynamical heating which increases the magnitudes of strong ENSO episodes. El Niño and La Niña are asymmetrical and related to the non-linearity of temperature changes and thus to the non-linear dynamics of sea level variation in the vicinity of the Equator and near the western coasts of North and South America. Coastal areas, however, can additionally experience non-linear sea level dynamics due to a potential non-Gaussian contribution introduced by the presence of possible outliers in altimetric observations.

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REFERENCES

- An S.-I., Jin F.-F. (2004) Nonlinearity and Asymmetry of ENSO, *Journal of Climate*, Vol. 17, 2399-2412.
- An S.-I., Hsieh W.W., Jin F.-F. (2005) A Nonlinear Analysis of the ENSO Cycle and Its Interdecadal Changes, *Journal of Climate*, Vol. 18, 3229-3239.
- Andersen O.B., Knudsen P. (2000) The Role of Satellite Altimetry in Gravity Field Modelling in Coastal Areas, *Physics and Chemistry of the Earth A*, Vol. 25, No. 1, 17-24.
- Anscombe F.J., Glynn W.J. (1983) Distribution of kurtosis statistic for normal statistics, *Biometrika*, Vol. 70, No. 1, 227-234.
- Antonov J.I., Levitus S., Boyer T.P. (2005) Thermosteric sea level rise, 1955-2003, *Geophysical Research Letters*, Vol. 32, L12602, doi:10.1029/2005GL023112.
- Bjerknes J. (1969) Atmospheric teleconnections from the equatorial Pacific, *Monthly Weather Review*, Vol. 97, 163-172.
- Burgers G., Stephenson D.B. (1999) The "Normality" of El Niño, *Geophysical Research Letters*, Vol. 26, No. 8, 1027-1030.
- Cane M.A. (1984) Modeling Sea level during El Niño, *Journal of Physical Oceanography*, Vol. 14, 1864-1874.
- Cazenave A., Cabanes C., Dominh K., Gennero M.C., Le Provost C. (2003) Present-day sea level change: observations and causes, *Space Science Reviews*, Vol. 108, 131-144.
- Cazenave A., Lombard A., Llovel W. (2008) Present-day sea level rise: A synthesis, *Comptes Rendus Geoscience*, Vol. 340, 761-770.
- Church J.A., White N.J. (2006) A 20th century acceleration in global sea-level rise, *Geophysical Research Letters*, Vol. 33, L01602, doi:10.1029/2005GL024826.
- Clarke A.J., Wang J., Van Gorder S. (2000) A simple warm-pool displacement ENSO model, *Journal of Physical Oceanography*, Vol. 30, No. 7, 1679-1691; Corrigendum *Journal of Physical Oceanography*, Vol. 30, No. 12, 3271.
- Clarke A.J. (2008) *An introduction to the Dynamics of El Niño & the Southern Oscillation*, Academic Press, Elsevier, Amsterdam, Boston, Heidelberg, London, New York, Oxford, Paris, San Diego, San Francisco, Singapore, Sydney, Tokyo.
- D'Agostino R.B. (1970) Transformation to Normality of the Null Distribution of G1, *Biometrika*, Vol. 57, No. 3, 679-681.

- DeCarlo L.T. (1997) On the Meaning and Use of Kurtosis, *Psychological Methods*, Vol. 2, No. 3, 292-307.
- Deng X., Featherstone W.E. (2006) A coastal retracking system for satellite radar altimeter waveforms: Application to ERS-2 around Australia, *Journal of Geophysical Research*, Vol. 111, C06012, doi:10.1029/2005JC003039.
- Douglas B.C. (2001) Sea level change in the era of the recording tide gauge, *Sea level rise: history and consequences*, eds. Douglas B.C., Kearney M.S., Leatherman S.P., Academic Press, San Diego, 37-64.
- Fu L.-L., Christensen E.J., Yamarone C.A. Jr., Lefebvre M., Ménard Y., Dorrer M., Escudier P. (1994) TOPEX/POSEIDON mission overview, *Journal of Geophysical Research*, 99(C12), 24369-24381.
- Hannachi A., Stephenson D.B., Sperber K.R. (2003) Probability-based methods for quantifying nonlinearity in the ENSO, *Climate Dynamics*, Vol. 20, 241–256.
- Hoerling M.P., Kumar A., Zhong M. (1997) El Niño, La Niña, and the Nonlinearity of Their Teleconnections, *Journal of Climate*, Vol. 10, 1769-1786.
- Hsieh W.W. (2004) Nonlinear multivariate and time series analysis by neural network methods, *Review of Geophysics*, Vol. 42, RG1003 / 2004, 1-25.
- Hunt B.G., Elliot T.I. (2003) Secular variability of ENSO events in a 1000-year climatic simulation, *Climate Dynamics*, Vol. 20, 689-703.
- Jevrejeva S., Grinsted A., Moore J.C., Holgate S. (2006) Nonlinear trends and multiyear cycles in sea level records, *Journal of Geophysical Research*, Vol. 111, C09012, doi:10.1029/2005JC003229.
- Jin F.-F., An S.-I., Timmermann A., Zhao J. (2003) Strong El Niño events and nonlinear dynamical heating, *Geophysical Research Letters*, Vol. 30, No. 3, 1120, doi:10.1029/2002GL016356.
- Joanes D.N., Gill C.A. (1998) Comparing Measures of Sample Skewness and Kurtosis, *The Statistician*, Vol. 47, Part 1, 183-189.
- Lafon T. (2005) JASON 1: lessons learned from the development and 1 year in orbit, *Acta Astronautica*, Vol. 56, 45-49.
- Kuragano T., Shibata A. (1997) Sea Surface Dynamic Height of the Pacific Ocean Derived from TOPEX/POSEIDON Altimeter Data: Calculation Method and Accuracy, *Journal of Oceanography*, Vol. 53, 585-599.
- Nerem R.S., Chambers D.P., Leuliette E.W., Mitchum G.T., Giese B.S. (1999) Variations in global mean sea level associated with the 1997-98 ENSO event: implications for measuring long term sea level change, *Geophysical Research Letters*, Vol. 26, 3005-3008.
- Niedzielski T., Kosek W. (2009) Forecasting sea level anomalies from TOPEX/Poseidon and Jason-1 satellite altimetry, *Journal of Geodesy*, Vol. 83, 469-476.
- Niedzielski T., Kosek W. (2010) El Niño impact on the probability distribution of sea level anomaly fields, *Polish Journal of Environmental Studies*, Vol. 19, No. 3, 605-614.
- Philander S.G. (1990) *El Niño, La Niña, and the Southern Oscillation*, Academic Press, San Diego.
- Röske F. (1997) Sea Level Forecasts Using Neural Networks, *Deutsche Hydrographische Zeitschrift – German Journal of Hydrography*, Vol. 49, No. 1, 71-99.

- Tziperman E., Stone L., Cane M.A., Jarosh H. (1994) El Niño Chaos: Overlapping of Resonances Between the Seasonal Cycle and the Pacific Ocean-Atmosphere Oscillator, *Science*, Vol. 264, 72-74.
- Wang C., Fiedler P.C. (2006) ENSO variability and the eastern tropical Pacific: A review, *Progress in Oceanography*, Vol. 69, 239-266.
- Wu A., Hsieh W.W. (2003) Nonlinear interdecadal changes of the El Niño-Southern Oscillation, *Climate Dynamics*, Vol. 21, 719-730.

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