Analysis and prediction of altimetric sea level variations during El Niño, La Niña and normal conditions

T. Niedzielski (1,2)**, W. Kosek** (1)

(1) Space Research Centre, Polish Academy of Sciences, Poland
(2) Institute of Geography and Regional Development, University of Wrocław, Poland

niedzielski@cbk.waw.pl /Fax: +48 71 3729372

Abstract

Recent developments in satellite altimetry are due to precise tracking and determining the satellite orbits. This is attained by such techniques as: Satellite Laser Ranging (SLR), Doppler Orbitograhy and Radiopositioning Integrated on Satellite (DORIS), and Global Positioning System (GPS). These techniques were adopted by American-French altimetric missions TOPEX/Poseidon (T/P), and Jason-1 (J-1). Satellite altimetry provides the accurate sea surface height (SSH) measurements. The SSH estimates and the long-term mean sea level are used to compute sea level anomaly (SLA) data. The SLA time series describe the dynamic sea level change. The SLA data provide the knowledge about the large-scale ocean circulation, including El Nino/Southern Oscillation (ENSO). The altimetric data obtained from T/P and J-1 measurements are used to compute the spectra of the SLA data as well as amplitudes of the most energetic oscillations in sea level variation as a function of latitude and longitude. These spectra and amplitudes were computed by the Fourier Transform Band Pass Filter (FTBPF). The SLA time series are often used to determine the trend of sea level change. These estimates may be derived both globally and regionally (for the dissimilar ocean areas). It is also possible to predict SLA data. The SLA predictions are computed using the combination of polynomial-harmonic least-squares and autoregressive models. The SLA forecasts can be used to predict ENSO events, because El Nino and La Nina signals are very well visible in SLA time series.

Introduction

The objective of this paper is to provide a comprehensive review of different approaches to the analysis of altimetric sea level change. In particular, the main focus is put on the relation between the regional sea level fluctuation and El Niño/Southern Oscillation (ENSO). It is now known that ENSO may cause extreme rise and fall of sea level in the vicinity of east and west equatorial Pacific. The magnitude of such variations may reach even 40 cm in respect to the long-term mean sea level. The analysis of sea level change includes both exploring the time series and forecasting. Exploring aims at detecting and understanding long-term and short-period variations in the sea level change. Prediction studies, on the other hand, use dissimilar models to determine the future sea level.

Long-term sea level change is usually described by a linear trend, fitted globally for the entire ocean and locally for selected ocean areas. Many authors calculated the rate of global sea level change using different data sets. They use both tide gauge time data (e.g. Gornitz and Lebedeff, 1987; Peltier and Tushingham, 1989; Douglas, 1991) and altimetric time series (e.g. Kosek, 2001; Leuliette et al., 2004). The rate of global sea level change determined from tide gauge records vary between 1.2 to 2.4 mm/year, depending on the data time span and the number of tide gauges under study. On the other hand, the rate of global sea level rise estimated using the altimetric time series are of the order of 2.8-3.5 mm/year depending mostly on the data time span. The minimum time span of altimetric data required to obtain the statistically significant trend with the probability close to 1 was found to be of 4.3 years (Niedzielski and Kosek, 2007). The rate of local sea level rise is very high in the western Pacific and may exceed 20 mm/year (Kosek, 2001). On the other hand, there is a fall of sea level (less than 10 mm/year) in the middle and eastern Pacific (Kosek, 2001).

Short-period oscillations are also present in sea level fluctuations. Nerem et al. (1994) found annual and semi-annual oscillations in sea level change. Their amplitudes depend on geographic region. Kosek (2001) found 183, 120, 90, 62, 37, 30 days oscillations in sea level fluctuations depending on the geographic region and determined the amplitudes of these harmonic terms. Niedzielski and Kosek (2005) also confirmed that the most energetic harmonic oscillations in global sea level change recorded by TOPEX/Poseidon altimetric satellite were annual and semi-annual components.

The above-mentioned findings lead to a better understanding of sea level variation and enable to determine both long-term and short-period predictions of sea level change. Warrick et al. (1996) forecasted that the global sea level may rise from 20 to 70 cm up to 2070. Röske (1997) predicted short-period sea level fluctuations by means of artificial neural networks. Chen et al. (1997) utilized the global hydrologic model to forecast annual and semi-annual non-steric sea level variation. Niedzielski and Kosek (2005) used time series methods to predict global sea level data obtained by TOPEX/Poseidon measurements. They have also predicted local sea level change in the east equatorial Pacific during ENSO and normal conditions (Niedzielski and Kosek, 2008).

In this paper we present and review our scientific results on the altimetric sea level change. We focus on long-term and short-period variations as well as on the prediction studies. The particular emphasis is put on the influence of ENSO on the local sea level change.

Methods

The mathematical methods used in our analyses to process altimetric sea level fluctuations can be divided into three groups. First, the long-term changes were analysed combining the stepwise simulation approach with testing statistical hypotheses. Second, the short-period oscillations in sea level change were extensively analysed by the signal processing techniques. Third, the prediction studies were performed using deterministic and stochastic time series modeling techniques.

Testing statistical hypotheses was used as a tool for detecting the statically significant trend in sea level rise. In fact, the main goal was to estimate the minimum sample size, i.e. the minimum data time span, required to obtain the statistically significant trend. The Cox-Stuart test for trend was utilized to test the null hypothesis of no trend in the data against the alternative hypothesis corresponding to the inclining trend. For details we relate to McCuen (2003). The stepwise algorithm was used to apply the Cox-Stuart test for different subsets of global sea level change time series. This allowed us to calculate the sample size for which the statistical significance of trend could be attained.

To analyse short period oscillations in sea level change the Fourier transform band pass filter (FTBPF) was applied (Kosek 2001). This filter enables computation of wideband oscillations with the power concentrated near some chosen central frequency. An oscillation computed by this filter has variable amplitude so this technique can be applied to compute time-variable amplitude spectra. It this paper this filter was applied to compute the averaged amplitudes of the chosen most energetic seasonal and subseasonal oscillations.

Forecasting sea level change was based on the polynomial-harmonic least-squares model and the stochastic uni- and multivariate autoregressive models. The deterministic polynomial-harmonic model described the trend, annual, and semi-annual components. The autoregressive model was fit to the residuals in order to predict its irregular variation. In particular, the irregularities in sea level change are driven by ENSO and thus can be captured by stochastic processes. The predictions were validated using root mean square error (RMSE) and mean absolute value (MAE). Different data time spans were selected to validate the forecasts. The global mean sea level change was predicted using uni- and multivariate autoregressive models fitted to the differenced data (Niedzielski and Kosek, 2005) and using polynomial-harmonic models combined with the univariate autoregressive models (Niedzielski and Kosek, 2008). Local sea level fluctuations were predicted on a grid scale using polynomial-harmonic model supported by the univariate autoregression (Niedzielski and Kosek, 2008).

Data

For the analysis, the gridded sea level anomaly (SLA) data recorded by TOPEX/Poseidon and Jason-1 altimetric satellites were chosen. SLA time series is calculated as the difference between the sea surface height (SSH) and the long-term mean sea level. The sampling interval of these data corresponds to one satellite cycle approximately equal to 10 days. The maximum data time span was 10.01.1993 - 14.07.2003, however for the computation of the mean prediction errors the time series was truncated in 2002. The spatial latitude-longitude resolution is of 1^o x 1^o. The spatial coverage includes all longitudes and is constrained to latitudes from 65 ^{o} S to 65 ^{o} N. Both global (averaged) and local (certain geographic regions) SLA data are processed in the analyses.

Results

In accordance with Niedzielski and Kosek (2007), for the purpose of the trend analysis the global mean SLA time series from TOPEX/Poseidon and Jason-1 were merged to cover the time period 10.01.1993 -14.07.2003. In the common observational period the data were combined and the bias between the two was removed. Two data sets were analysed independently: (1) the global mean SLA time series, and (2) the non-seasonal global mean SLA data, i.e. the difference between the global mean SLA time series and the corresponding least-squares model for annual and semi-annual harmonic components. The Cox-Stuart test supported by the above-mentioned stepwise iterative procedure was applied. Thus, the minimum time span of altimetric data required to obtain the statistically significant trend in sea level rise was estimated. The results indicated that at least 4.3 years of the data time span were needed to capture the trend with the probability close to 1 (Tab. 1). This data time span becomes higher if the least-squares model is not subtracted from the SLA data (Tab.1). It was also noted that it was not possible to detect acceleration in SLA data, because of too short data time span.

Table 1. The minimum time span of altimetric data required to detect a statistically significant trend in sea level rise. Source: Niedzielski and Kosek (2007).

Data	Minimum sample size [cycles]	Minimum sample size [years]
Global SLA	203	5.5
Non-seasonal global SLA	160	4.3

Following Kosek (2001), the mean amplitudes of oscillations were computed using the above-mentioned FTBPF amplitude spectrum for gridded SLA data. The 30, 62, 90, 120, 182, 365 day oscillations were detected and the spatial variation of their mean amplitudes was determined for the entire geographic coverage provided by TOPEX/Poseidon and Jason-1 (Fig. 1). It is clearly seen that the annual, semi-annual and triennial oscillations are the most energetic at the equatorial regions as well as north-west Pacific ocean. The annual oscillation is also energetic in north-west Atlantic region, and the semi-annual oscillation has the greatest amplitudes in the west and east equatorial Indian ocean. Big amplitudes of the 62-day oscillation are caused mostly by inaccurate modeling of M_2 tide amplitudes in some coastal regions. Some equidistant spots above the equator in the central Pacific ocean for the 30-day oscillation represent the tropical instability waves or Legeckis waves (Cox, 1980) with the amplitudes of the order of 1 cm.

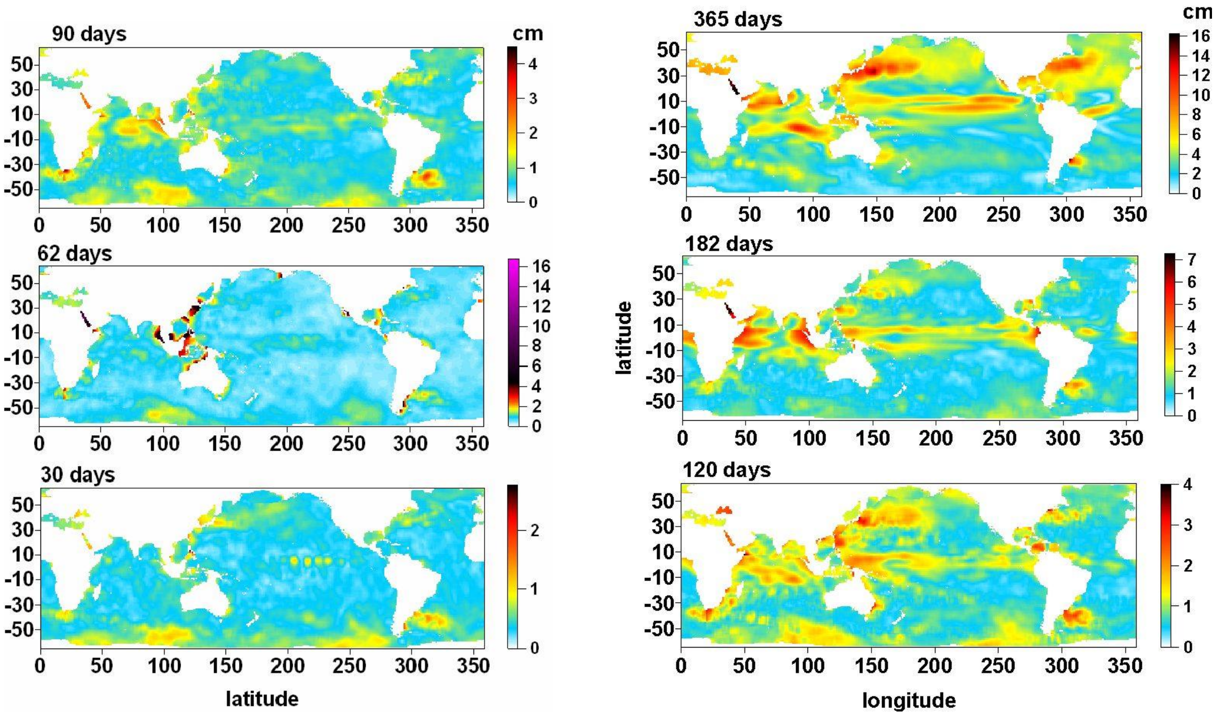

Figure 1. Mean amplitudes of 90, 62 and 30-day oscillations (left column) and 365, 182 and 120-day oscillations (right column) computed by the FTBPF in the SLA data of TOPEX/Poseidon and Jason-1.

The deterministic SLA prediction was based on the 3-step (1-month) extrapolation of the polynomial-harmonic least-squares model consisted of the trend, annual, and semi-annual oscillations. This model provided the reasonable overall fit to the data. The stochastic forecast of the SLA residuals (the data minus polynomial-harmonic model) was based on the 3-step ahead autoregressive prediction. The prediction of global SLA data can only be used as the general future scenario (Niedzielski and Kosek, 2005; 2008). However, the prediction of local sea level change in the eastern equatorial Pacific determined using both polynomial-harmonic model extrapolation and the autoregressive prediction was considered particularly useful in forecasting ENSO signal (Niedzielski and Kosek, 2008). The significant reduction in the prediction error was observed and hence the potential applicability of altimetric data in ENSO studies was highlighted (Tab. 2).

Table 2. The SLA prediction error reduction for ENSO and normal conditions.

Validation period	**Ratio between the RMSE and maximum amplitudes of the signal**
El Niño 1997/1998	~1/3
La Niña 1998/1999	~1/4
Normal conditions	~1/6

Conclusions

The trend of sea level change may be detected with the probability close to 1, for small significance levels of the Cox-Stuart test after 160 satellite cycles (approx. 4.3 years). The 30, 62, 90,120,182, 365-day oscillations of SLA data are estimated. Most of the energy of the annual, semi-annual, and triennial oscillations are concentrated in the equatorial regions of the Pacific, Indian and Atlantic oceans. The combination of a polynomial-harmonic model and an autoregressive model allows one to improve the accuracy of SLA predictions in the east equatorial Pacific in respect to those computed by means of a pure polynomial-harmonic model. This improvement is noticed during El Niño, La Niña and normal conditions.

Acknowledgements

The research is financed by the Polish Ministry of Education and Science under the project No 4 T12E 039 29. Tomasz Niedzielski was supported by the Foundation for Polish Science within the Start Programme (stipends for young researchers) and by European Union within the Marie-Curie Actions. The authors thank the Center for Space Research, University of Texas at Austin, USA for providing the T/P and J-1 data. The authors of R 2.0.1., a Language and Environment 2004 and the additional packages are acknowledged.

References

Chen, J.L., Wilson, C.R., Chambers, D.P., Nerem, R.S., Tapley, B.D., *Seasonal global water mass budget and mean sea level variations*, Geophys. Res. Lett. 25, 3555—3558, 1998.

Cox, M., *Generation and Decay of 30 day waves in the numerical model of the Pacific*, J. Physical Oceanography 10, p. 11681—11686, 1980.

Douglas, B.C., *Global sea level rise,* Journal of Geophysical Research 96, p. 6981—6992, 1991.

Gornitz, V., Lebedeff S., *Global sea-level changes during the past century,* In: Nummedal D. et al. (Eds.) Sea-level fluctuation & coastal evolution. Soc. Econ. Paleontol. Miner. Spec. Publ. 41, p. 3—16, 1987.

Kosek, W., *Long-term and short period global sea level changes from TOPEX/Poseidon altimetry*, Artificial Satellites 36, p. 71—84, 2001.

Leuliette, E.W., Nerem, R.S., Mitchum, G.T., *Calibration of TOPEX/Poseidon and Jason Altimeter Data to Construct a Continuous Record of Mean Sea Level Change*, Marine Geodesy 27, p. 79—94, 2004.

McCuen, R.H., Modeling Hydrologic Change, Statistical Methods, Lewis Publishers, Boca Raton, London, New York, Washington, D.C., 2003.

Nerem, R.S., Schrama, E.J., Kobylinsky, C.J., Beckley B.D., *A preliminary evaluation of ocean topography from the TOPEX/POSEIDON mission*, Journal of Geophysical Research 99(C12), p. 24565—24583, 1994.

Niedzielski, T., Kosek, W., *Multivariate stochastic prediction of the global mean sea level anomalies based on TOPEX/Poseidon satellite altimetry,* Artificial Satellites 40, p. 185—198, 2005.

Niedzielski, T., Kosek, W., *A required data span to detect sea level rise*, In: Weintrit, A. (Ed.), Advances in marine navigation and safety of sea transportation, p. 367—371, Gdynia Maritime University, Gdynia, 2007.

Niedzielski, T., Kosek, W., *Forecasting sea level anomalies from TOPEX/Poseidon and Jason-1 satellite altimetry*, Journal of Geodesy, DOI: 10.1007/s00190-008-0254-5, 2008.

Peltier, W.R., Tushingham, A.M., *Global sea level rise and the Greenhouse Effect: might they be connected?* Science 244, p. 806—810, 1989.

Röske, F., *Sea level forecasts using neural networks*, Ocean dynam. 49, p. 71—99, 1997.

Warrick, R.A., Le Provost, C., Meier, M.F., Oerlemans, J., Woodworth, P.L., *Changes in sea level*, In: Houghton, J.T., Meira Filho, L.G., Callander, B.A., Harris, N., Kattenberg, A., Maskell, K., (Ed.) *Climate change 1995. The science of climate change*, p. 361—405, Cambridge University Press, Cambridge, 1996.