Common Features of the Sea Level Records from Baltic Tide Gauges

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Abstract

Tide gauge data provide information on sea level variations as well as on the vertical land movements at tide gauges. It is also useful for geoid modelling in coastal regions. Sea level records from a number of tide gauges in the Baltic Sea were analysed in the framework of the project on a cm geoid in Poland.

Data from each tide gauge has been expressed as a sum of four components: a tide gauge constant, a linear trend, a regional component and a local component. The regional component represents the variations of sea level that are common for all tide gauges. The local component consists of local systematic effects, signal and a noise that are, however not clearly separated in the present analysis.

Tide gauge data with monthly resolution was first detrended and then averaged over a chosen sample of sites resulting in the determination of regional component. Correlations between regional component and individual site data were investigated. High level of correlations obtained indicates strong common features in tide gauge records. It proves the adequacy of the model used in the present analysis. The regional component was used for recursive determination of trend and the local component at each site. Estimated trend indicates vertical land movement at a site. Common features in local components of two groups of sites were observed.

1. Introduction

Sea level determined from tide gauge records is closely related to the equipotential surface of the Earth gravity field, namely the geoid, and as such it is used as reference in height systems all over the world. Due to numerous factors that originate in varying ocean and atmosphere dynamics as well as in time-varying gravity field, the sea level exhibits substantial temporal variations and it cannot be determined from the tide gauge observation at single epoch. Modelling those effects poses real problem and so far the efficient models do not exist. Therefore the sea level used as reference for vertical datum is determined as the average of tide gauge measurements over a period sufficiently long to smooth out most of disturbing effects. Such averaged sea level is called mean sea level. Moreover vertical displacements of land that are substantial in some regions, affect tide gauge records. Levelling data as well as data from permanent GPS stations operating in the vicinity of tide gauges are useful to separate vertical land displacements from tidal records. Although data from satellite altimetry and gravity missions provide recently global monitoring of sea level, the tidal gauge records bring still valuable information on sea level variations in coastal regions that substantially complete global sea level monitoring. Tide gauge records are also used for interpretation of gravity variations using super-conducting gravimeters (Virtanen and Mäkinen, 2002) as well as for calibration of satellite surveying systems (Woodworth, 1997), in particular satellite gravity data. They are still, however widely used for investigating oceanographic and geophysical phenomena in many regions worldwide. Baltic Sea area as a specific one from geotectonic point of view was for decades the object of extensive research. The interest of research teams has in particular been focused on variations of sea level derived from tide gauge data. Tidal data was either analysed in detail separately for each station (van Onselen, 2000) or a combined data analysis from a group of stations was done (Vermeer et al., 1988) when the similarity of time series from different tide gauges was used for determining the simplest regional model (plane fitting in space domain and trend fitting in the time domain). The residuals obtained for all tide gauges investigated allow for detection of possible small vertical motions of sites with respect to one another. Dependence on physical parameters such as air pressure variations and the effect of the Baltic water balance was investigated too. It was shown that the complexity of the relations between mean sea level of the Baltic Sea and other physical factors does not result in any simple model for corrections to the tide gauge observations. The spectral analysis of the Finnish tide gauge data exhibited rather white spectrum besides the prominent annual peak. Confidence limits for a white noise spectrum were calculated for each site spectra. The probabilities of the occurrence of the highest peaks were also close to those predicted from white noise. Similarity of the spectra can be explained by strong correlations inevitably present in tide gauge time series

from one, near-landlocked sea (all Baltic tide gauge

time series).

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The increase of that similarity towards the North indicates the existence of strong correlations between the tide gauge records in the Gulf of Bothnia. The analysis resulted in the estimation of land uplift parameters for Finnish tide gauge stations (Vermeer et al., 1988). They are used as reference values for the numerical tests conducted in this work. Ten years later the further analysis of Finnish tide gauges data in terms of studying its statistical characteristics was performed (Johansson et al., 2001).

The analysis of Baltic Sea level indicated the existence of inter-annual sea level variation that exhibits a distinct geographical pattern (Ekman, 1996). The maximum of those variations occurs in the inner parts of both gulfs, the Gulf of Bothnia and the Gulf of Finland while the minimum occurs in southwestern Baltic close to Kattegat; the maximum is 3 times larger than the minimum. The seasonal sea level variations of periods of 12 and 6 months as well as the "pole tide" of the period of 14.3 months turn out to have patterns almost identical to that of the inter-annual variation. Thus all sea level variations on timescales form months to years in the Baltic Sea and its transition area to the North Sea are found to obey a common pattern. That indicates that they, to a large extent, should have a common origin that presumably is a wind stress.

In the majority of research related to the tide gauges data analysis, the difficulty in modelling and prediction of sea level variations was addressed. One of a few exceptions is the publication (Ivanov, 2002) that rather should be considered as an example of scientific numerology than scientific research. Numerous spectral peaks observed in the spectra of variations of meteorological parameters and sea level were explained by the author as the effect of planets of the solar system, the Sun eclipses and minor irregularities in the orbital motion of the Moon. It is quite obvious, however that in a spectrum of variations of sea level that in general behave like a white noise (Vermeer et al., 1989) it is possible to find a term of any period. especially when using non-linear model. Neither common sense nor practical experience authorize to agree with the statement of the author of quoted work: "Variations of meteorological parameters are due in large part to periodic processes and can be forecast for several years" (Ivanov, 2002).

A representation of sea level variations as a sum of a well fitted model and a residual component seems appropriate in analysis of tidal records to avoid misinterpretation of the investigated phenomena. Therefore an attempt to construct an empirical model of variations of the Baltic Sea level was undertaken in the present work. The concept of the model is based on the observed similarity in time series from all Baltic tide gauges that reflects the existence of distinguished component common for the records from all sites investigated. That component could be considered as the variation of Baltic Sea level in total, what is nothing but a regional variation of a sea surface. Besides the regional component each record consists also of the component representing local features of sea level variations. The residual components consist of

- a linear trend, being a consequence of vertical movement of land with respect to sea level;
- residuals, being the consequences of the local specific arrangement of tide gauges.

Due to the mentioned absence of significant correlation between time series of sea level variations and accessible time series of regional active physical parameters (atmospheric pressure, air temperature, water salinity etc.) the model based exclusively on accessible tide gauge data (http://www.pol.ac.uk/psmsl/psmsl_individual_stations .html) was used.

2. Regional model of Baltic Sea level

A preliminary statistical analysis of the chosen time series of tide gauge data was carried out considering the results of similar works (e.g. Spencer and Woodworth, 1993). The dispersion was found stationary for all tide gauges at the reasonable confidence level. Monthly value at each station, vary linearly with different rate on the background of noiselike process.

Tide gauge data with monthly resolution from 15 Baltic sites was first de-trended and then averaged over a chosen sample of sites, resulting in the determination of regional component. Correlations between regional component and individual site data, including sites that did not contribute to the determination of regional component, were investigated. High level of correlations obtained indicates strong common features in tide gauge records. It proves the adequacy of the model used in the present analysis. The location of tide gauges investigated and the examples of regression dependences are given in Fig. 1.



 Fig. 1. Location of tide gauges along the coast of the Baltic Sea with the examples of correlation between regional component and individual site data. Sites used for the model determination marked (•); sites used for testing the model marked (x)

High correlation between the original tidal signal and the regional component obtained for all tide gauges investigated allows for considering the computed regional model as site-independent and representing the behaviour of the level of Baltic Sea as a whole. The research has thus been carried out in two directions. One concerns the investigation of the variations of a sea level as a whole. The other concerns variations, specific at individual site and consisting of the sum of "residual" periodic or nearly periodic changes of a sea level and monotonous vertical movement of the land.

In the present paper some results obtained by studying both approaches are shown. Long time series of regional model based on data records from about 200 years has allowed for conducting spectral analysis in a wide range of the periods and for ensuring the steady spectral estimations of seasonal components. Fig. 2a shows a periodogram of the regional model in the maximum range of periods. Interpolation of spectral components with varying length of a time series was applied for construction of the periodogram. Spectral estimations were made by a discrete Fourier transformation with smoothing in frequency domain. Fig. 2b shows a periodogram in the range of periods up to 2 years with estimations of errors of calculated components.



Fig. 2. Periodograms of the regional model of Baltic Sea level variations based on 200 years data (a) and based on averaging of partial periodograms of segments of time series (b)

Due to the stability in time and frequency domain of the regional model based on data from German, Swedish, Polish and Finnish tide gauge stations, it was possible to show the presence of two parts of a spectral background of the seasonal components. These two parts are represented by a white noise in a range of periods from one year up to two hundred years as well as by a flicker-noise (1/f) with sub-annual periods. In the case of a white noise spectrum, accumulating observations with time eventually leads to the stabilisation of the mean sea level estimation on the intervals of several years and longer.

Noise-like character of a spectrum of tide gauge records does not allow for an effective use of results of spectral analysis, for example for predicting. Spectral analysis of time series corresponding to the regional model of Baltic Sea level variations shows the presence of three distinct seasonal components of annual, semiannual and Chandler periods (Fig. 3a).



Fig. 3. Periodogram of variations of the Baltic Sea level (a) and the rms of estimated amplitude of spectral components (b)

The estimated amplitudes of those components equal to 9 cm, 4 cm and 3 cm, respectively. They correspond to the amplitudes obtained by other authors (e.g. Vermeer et al., 1989). Variation of accuracy of the estimation of the amplitudes shown in Fig. 3b corresponds to the variation of the amplitude.

Thus, the broadband (frequency range of about 10^3) noise-like character of regional model makes the use of filters in frequency domain for analysis of separated components difficult.

3. Rate of trend estimation from tide gauge records

Analysis of regional sea level model in both time and frequency domains showed that on timescales from single years to a hundred years the model behaves as a noise-like process stationary in terms of the mathematical expectation of mean value. Subtraction of the model from initial data should not affect parameters of linear trend estimated from the residual time series. Namely, both trend and rate of trend should remain unchanged after subtracting the model. On the other hand a substantial reduction of dispersion of parameters provided by residual time series is expected. Those features of the model were examined using tidal records from numerous sites, including those that did not contribute to the model.

The effect of removing regional model from the time series from the tide gauge that did not contribute to the model is shown in Fig. 4.

Fig. 4 shows that removing the regional model from the time series of individual tide gauge makes it possible to estimate the rate of trend with substantially smaller errors. The results obtained compared with those from literature show for the majority of tide gauge records the coincidence in estimations of rate of change of the sea level within $\pm \sigma$. The coincidence is affected by the fact of different intervals of records available from tide gauges as well as different lengths of data records.

A choice of the most "correct" estimation of trend seems still a problem and different authors apply different approaches. Hopefully more reliable estimations of rate of change of sea level may be obtained when using besides tide gauge data also independently acquired measurements such as levelling data or data from space geodetic systems.



Fig. 4. The effect of removing the regional model from the time series of Landsort tide gauge

A simple and evident technique of estimation of rate of trend and average sea level is used in this work. In the technique the average value over a variable window length with the fixed starting or ending epoch, called a progressive total window (PTW) is determined. Fixing the ending epoch is more commonly used due to practical needs for mean sea level determination. The determination of the minimum length of such window required for reliable sea level estimation was one of the tasks of present research.

The average and median of sea level vs. the length of a progressive total window for Warnemünde2 tide gauge data are shown in Fig. 5.



Fig. 5. The average and median vs. the length of a progressive total window for Warnemünde2 tide gauge

Fig. 5 shows that both average and median practically coincide and the estimated error of average becomes smaller then 5 mm if the length of PTW exceeds 25 years. To confirm stability of a 5 mm level of accuracy the error of average was directly estimated (Krynski and Zanimonskiy, 2003). The dependence of rms of average and rms of monthly data on the lengths of data records for Warnemünde2 (a) and Wladyslawowo (b) is shown in Fig. 6.

External accuracy of sea level estimation represented by rms of a sea level averaged over 20 - 25 years equals to 5 mm (Fig. 6) and coincides with internal accuracy of its estimation (Fig. 3). Just as it was shown for case of time series of GPS solutions (Krynski and Zanimonskiy, 2003, Krynski et al., 2003) there is a characteristic bend of curve on the diagrams (Fig. 6).



Fig. 6. The rms of mean in windows and mean rms monthly data within windows vs. window length for Warnemünde2 (a), and Wladyslawowo (b); autocorrelation of Wladyslawowo tidal record (c)

The difference is that in case of tide gauge data the bend corresponds to one-year data window (in GPS solutions it was one day) and is less distinguished. The bend is connected with shown in Fig. 2 break of a line that approximates the tendency of a spectral background.

Fig. 6 shows also the dependence of the rms of mean as internal accuracy (parameter $\sigma/n^{1/2}$) on the length of the window. The internal accuracy, as it frequently happens in practice, turns out approximately 1.5-2 times better, than the rms of means that represents the external accuracy. At length of data series over ten years, internal and external accuracy asymptotically coincide. It shows that time series of tide gauge data are not quite random and that monthly-averaged data are correlated (Fig. 6c).

In the present work the seasonal effects are not examined since they practically do not affect the rate of trend and average sea estimated from long series (not less than 5-10 full years) of tide gauge data.

Statistics of tide gauge records at individual sites, shown on the graphs in Fig. 6, exhibit a distinguished similarity. Such similarity represents the majority of the Baltic stations. It corresponds to similarity of time series addressed already in literature, e.g. (Vermeer et al., 1988; Ekman, 1996).

The examples of use of a progressive total window for determination of rate of change of a sea level at individual sites are shown in Fig. 7.



Fig. 7. Estimation of rate of change of a relative sea level with use of a progressive total window (max 25 years) in Wladyslawowo (a) and Stockholm (b)

The rate of trend at Stockholm is estimated within the range of -4.05 mm/year up to -3.66 mm/year. It is in agreement with estimations given in literature (e.g. Wöppelmann et al., 2000). At Wladyslawowo the estimations of rate of trend vary from 1.75 mm/year up to 3.34 mm/year while Wöppelmann estimated it as smaller by 0.3 mm/year (Wöppelmann et al., 2000).

Fig. 7 shows the dependence of the dispersion of estimated rate of change of sea level on the length of data record examined. The dispersion can vary from 5% for 110 years long data record, up to 30% for the 50 years long data series. Reduction of dispersion of the initial data represented by monthly average makes possible to more accurately and reliably estimate the rate of change of sea level. Such reduction of dispersion might be achieved by removing regional model from time series. The model should certainly be checked up on the absence of linear trend in it. The results of model examination with use of a progressive total window for determination of rate of trend in regional model are shown in Fig. 8.



Fig. 8. Rate of trend in regional model estimated with use of a progressive total window of 25 years

Fig. 8 shows that the rate of trend in regional model does not exceed 0.2 mm/year. It is worth to note that the results given in Fig. 8 refer to tide gauge records since 1887 when at least 4 tide gauges were operating at the coast of Baltic Sea.

The examples of rate of trend of the sea level estimation with use of a progressive total window to the residuals after removing regional model are shown in Fig. 9.



Fig. 9. Estimation of rate of trend of sea level with use of progressive total window (max 25 years) to residuals after removing regional model at Wladyslawowo (a) and Stockholm (b)

Rates of trend estimated with dispersion of ± 0.05 mm/year at Stockholm and of ± 0.23 mm/year at Wladyslawowo (Fig. 9) coincide with those obtained by Wöppelmann (Wöppelmann et al., 2000) except the dispersions at the sites are reduced by a factor 3.

4. The role of the regional model in effective implementation of short tidal records for the determination of sea level

Stationary behaviour of the regional model is of particular importance for investigations of sea level variations using combined satellite and tide gauge data. Sea level variations obtained from satellite data are affected by small random errors and they exhibit high temporal resolution. They require, however calibration with use of terrestrial data. Time series of satellite solutions of a length of a few decades is unfortunately much shorter than those of tide gage records that at some sites exceed even 200 years. Uncertainty of rate of change of mean sea level determined from satellite data reaches 1.5-2 mm/year. The use of regional models seem to allow in the nearest future for determination of mean sea level from tide gauge records with similar accuracy and temporal resolution as it is done using satellite data.

The rms of rate of trends of Baltic Sea level computed from tide gauge data over a data window of different length with use of PTW method and compared with literature data as well as accuracy of satellite methods is shown in Fig. 10.

Fig. 11 shows the dependence of errors of average sea level estimation at Wladyslawowo on the length of window (the case represented by two upper curves was already shown in Fig. 6b). Removing a regional model results in substantial decrease of dispersion of residuals as well as in reduction of the errors of mean sea level estimation. Thus, the application of regional model makes it possible to reduce from 20 years to even 10 years the length of data record required for determination of sea level with 1 cm accuracy. Accuracy of 1.5 cm could already be achieved when processing 2-3 years long data record with use of regional model. Otherwise 10 years data record is needed. The implementation of regional model enables participation of sites with relatively short tide gauge data records in research programs on studying Baltic Sea level variability and kinematics of land uplift in the region.



Fig. 10. The rms of rate of trends of Baltic Sea level computed over a data window of different length with use of PTW method and compared to the rms averaged over 5 stations: Newlyn, Aberdeen II, Hoek van Holland, Esbjerg and Bergen (Woodworth, 1997)



Fig. 11. The rms of mean sea level over a data window with and without removing regional model vs. window length

Conclusions

- 1. Statistics of tide gauge records at individual sites exhibits a distinguished similarity. Such similarity represents the majority of the Baltic stations.
- 2. High correlation between the original tidal signal and the regional component obtained for all tide gauges investigated allows for considering the computed regional model as site independent and representing the behaviour of the level of Baltic Sea as a whole.
- 3. Removing regional model results in substantial decrease of dispersion of residuals as well as in reduction of the errors of rate of trends and mean sea level estimation on Baltic tide gauges.
- 4. The implementation of regional model enables the participation of sites with relatively short tide gauge data records in research programs on studying Baltic Sea level variability and kinematics of land uplift in the region.

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