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Tide gauge records-derived variations of Baltic Sea level in terms of geodynamics

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Abstract: Sea level monitoring at tide gauges plays an important role in geodesy, geodynamics research and oceanography. It provides data for referencing vertical datum, for modelling geoid in coastal regions, for determination of vertical land movements and for studying ocean dynamics. Investigation of Baltic Sea level variations is considered an important component of geodynamics research in Central and Northern Europe. The analysis of tide gauge records from Baltic sites was conducted in the framework of the project on a cm geoid in Poland. Those records showed strong common features that were further used for deriving the model of Baltic Sea level variations. High level of correlations of the model with individual site data proved its adequacy. Regional characteristics of the model were investigated using regression and correlation analysis. It was shown that the model represents very well both global and regional features of Baltic Sea level variations. The use of the model as reference to investigate local features of tide gauge records that reflect site-specific variations of sea level was also discussed. Spectral analysis of the model of Baltic Sea level variations indicates the existence of distinguished term of Chandler period besides two major terms of annual and semi-annual periods. The existence of polar motion component in Baltic Sea level variations was investigated using correlation analysis. Also the land vertical movement derived from Baltic tide gauge data was determined and compared with literature data.

Keywords: Sea level, tide gauge, land uplift, geodynamics, polar motion

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1. Introduction

Last fifty years has brought a dramatic progress in modelling the Earth's gravity field, mainly on global scale but also on regional and local scales as well as in geodynamics research. High precision satellite altimetry as well as precise GPS positioning combined with terrestrial data allow for modelling gravity field and corresponding geoid at sub-decimetre level. Determination of geoid with accuracy at a cm level became actually a challenge for researchers. Traditionally, the gravity field has essentially been considered as static over human lifetimes (Dickey, 2000). Its non-static component that corresponds to less than 1% of the gravity field exhibits variations on timescales ranging from hours to thousands of years. Those temporal variations are caused by surface mass redistribution including tides, long-term aquifer depletion and post-glacial rebound as well as variations of mass within the atmosphere.

After over 30 years of extensive research and technical preparations, the growing needs for high-resolution precise gravity field model materialized in a series of Earth's gravity field-dedicated space missions: CHAMP – started in 15 July 2000, GRACE – started in 17 March 2002, and planned for 2006 GOCE mission (Krynski, 2001). The results of the GRACE mission provide for the first time the estimation of temporal variations of the Earth gravity field (beyond the dynamical flattening and the pear-shape coefficient) on a global scale to a rather high spatial resolution. A scientific challenge is that of separating the observed total signal from GRACE enriched with that acquired during the GOCE mission according to the temporal and spatial variability of the various sources like mass changes or mass motion related to sea level, hydrology, glaciology and solid Earth.

Of particular interest is the investigation of sea level changes and post-glacial rebound. Although data from satellite altimetry and gravity missions allow for the separation of the steric and mass components of sea level rise variations, including secular change, the tidal gauge records bring still valuable information on sea level variations in coastal regions that substantially completes its global monitoring (Krynski et al., 2004). Tide gauge records are widely used for investigating oceanographic and geophysical phenomena in many regions worldwide. Besides for monitoring sea level variations they 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. Due to the complexity of sea level variation phenomena, its modelling is not an easy task and so far the efficient models do not exist.

Investigation of Baltic Sea level variations is considered an important component of geodynamics research in Central and Northern Europe. Baltic Sea area as a specific one from geotectonic point of view was for decades the object of extensive research using uniquely long tidal records from densely and almost uniformly distributed stations. In particular the Fennoscandian land uplift was widely investigated using different combinations of tidal data, gravity, levelling, GPS, altimetry and geological data. In terms of sea level variations Baltic Sea exhibits specific features as being a unique nearly land-locked sea. Tide gauge data was either considered in terms of individual data records (e.g. Wróblewski, 2001), as complex studies of data from individual sites and groups of sites with simulated data (e.g. van Onselen, 2000) or the analyses of data from groups of stations were performed (e.g. Vermeer et al., 1988) when the simplest regional model (plane fitting in space domain and trend fitting in the time domain) was generated using the similarity of time series from different tide gauges. It was shown that the complexity of the relations between mean sea level of the Baltic Sea and other physical factors, e.g. air pressure variations and the effect of the Baltic water balance, does not result in any simple model for corrections to the tide gauge observations.

The analysis of Baltic Sea level based on tidal records from numerous sites around the sea basin showed the existence of inter-annual sea level variation (Ekman, 1996). That variation exhibits a distinct geographical pattern with the maximum in the inner parts of gulfs, the Gulf of Bothnia and the Gulf of Finland and the minimum in southwestern Kattegat. The seasonal sea level variations of periods of 12 and 6 months as well as the "pole tide" of 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 timescale ranging form months to years in the Baltic Sea and its transition area to the North Sea are found to obey a common pattern. Ekman presumes a common origin of those variations, to a large extent, in terms of a wind stress. Wind stress as well as atmospheric pressure effects on sea level variations were discussed in (Wróblewski, 2001).

The majority of the tide gauge data analyses address the difficulty in modelling and prediction of sea level variations. Quantitative analyses of tidal records were strongly biased by a lack of such model. The authors of this paper made an attempt to construct an empirical numerical model of variations of the Baltic Sea level. The representativeness of the model was investigated. The model was also used to study local and regional features of tide gauge records as well as to estimate land uplift in the Baltic region. Also the existence of polar motion component in Baltic Sea level variations was investigated using correlation analysis.

2. Modelling Baltic Sea level variations

The concept of the Baltic Sea Level Model (BSLM) developed is based on the observed similarity in time series from all Baltic tide gauges. Averaging tidal records from different sites leads to almost free of site-dependent noise time series that represent local sea level variations up to a scale factor. A representation of sea level variations as a sum of a well-fitted model standing for the scaled component common for the records from all sites investigated, and residual components representing local features of sea level variations, seems appropriate in analysis of tidal records. The model could therefore be considered as the representation of temporal variation of Baltic Sea level with time-independent spatial distribution of its scale factor. The residual components reflect a linear trend that is a consequence of vertical movement of land with respect to sea level, and residuals that are the consequences of the local specific arrangement of tide gauges.

Monthly averaged tide gauge data accessible on the web site of the Permanent Service of Mean Sea Level (PSMSL) was used. Tidal data from 15 sites representative for the Baltic Sea basin with possibly long records (from 190 to at least 50 years) were chosen for generating the empirical numerical model in the form of time series and scale factor spatial distribution. Its terms were obtained by averaging the de-trended and stacked records from individual stations. Linear trend in time series of tide gauge data was eliminated using least squares algorithm. Stacking and averaging the source data in time domain and interpolating the scale factor in space domain results in BSLM.

The procedure of generating the model can be briefly described as follows. Sea level record h_{ki} from site k at t_i epoch is considered as a function of φ_k, λ_k co-ordinates of site k:

$$h_{ki} = h(\varphi_k, \lambda_k, t_i)$$

The BSLM at the inner sea grid point with co-ordinates φ_j, λ_j *at* t_i epoch was expressed in the form:

$$H_{ij} = \hat{H}(\varphi_j, \lambda_j) \cdot \tilde{H}(t_i)$$

where $\hat{H}(\varphi_j, \lambda_j)$ is the 2D distribution of time-independent scale factor and $\tilde{H}(t_i)$ is a time series of temporal component of BSLM.

Temporal component of BSLM was obtained by stacking and averaging tidal records from individual sites as follows

$$\widetilde{H}(t_i) = \frac{1}{n_i} \sum_{k=1}^{n_i} h_{ki}$$

with

$$n_i = \sum_{k=1}^{N} (h_{ki})^0$$

where n_i is the number of valid readings at the t_i epoch in the records from N tidal gauges used for generating the model.

The model obtained reflects major temporal and spatial characteristics of Baltic Sea level variations. Scale factors at the sites correspond to regression coefficients of tidal records with respect to the model time series. Time series of the model derived as well as the examples of de-trended records from a few tide gauges for 10 years interval are shown in Fig. 1. Some properties of BSLM in time and frequency domain are discussed in the Section 5.

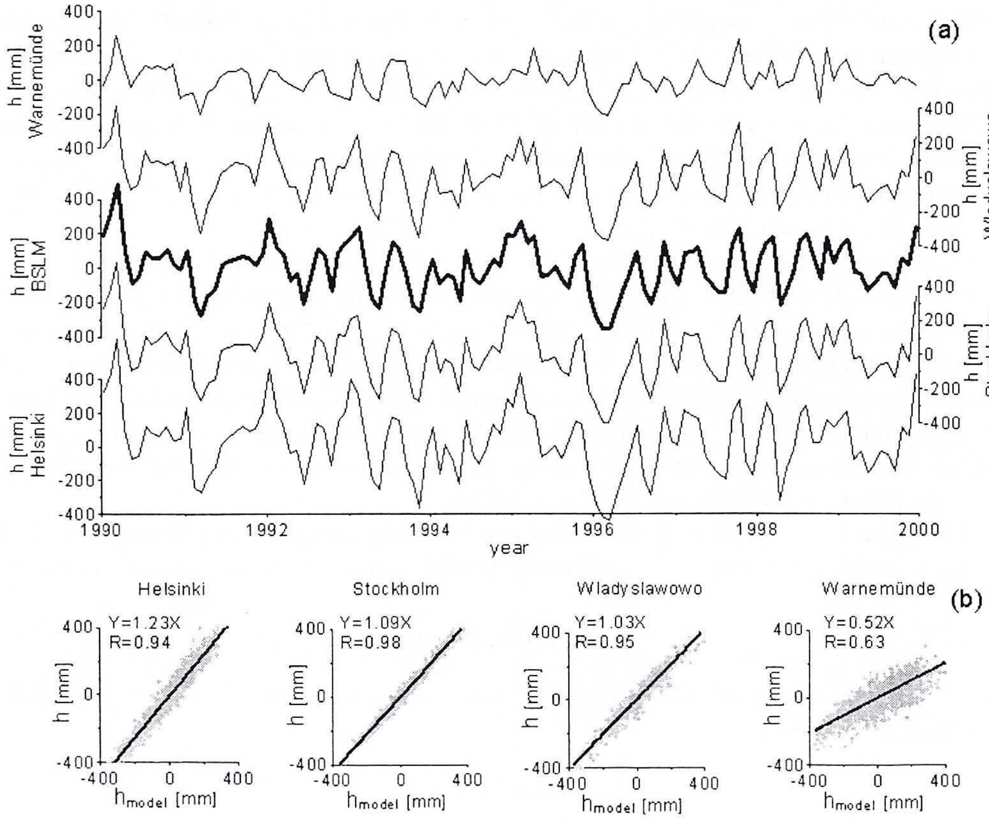

Fig. 1. De-trended records from Warnemünde, Wladyslawowo, Stockholm and Helsinki tide gauges and time series of BSLM (a), and corresponding regression plots (b)

All Baltic Sea area tide gauge records exhibit an evident similarity. They are also very well mutually synchronized. The coefficients of regression and correlation of data record with the model are site-dependent. Processing tidal data of higher temporal resolution, e.g. daily or even weekly means, could result in the improvement of estimation of statistical parameters of data records (e.g. Johansson et al., 2001) and also lead to a better fitted model.

3. Regional and local characteristics of Baltic Sea Level Model

Comparison of BSML with tide gauge records allows for determination of regional characteristics of the model. In particular, regional variability of sea level and goodness of the BSLM fit to data records can be examined on the bases of regression and correlation analysis, respectively. The maps of regression coefficient and correlation coefficient based on data estimated at the marked tide gauges are shown in Fig. 2a and Fig. 2b, respectively. The regression coefficient and correlation coefficient along Baltic Sea central waterline profile are given in Fig. 3a and Fig. 3b, respectively.

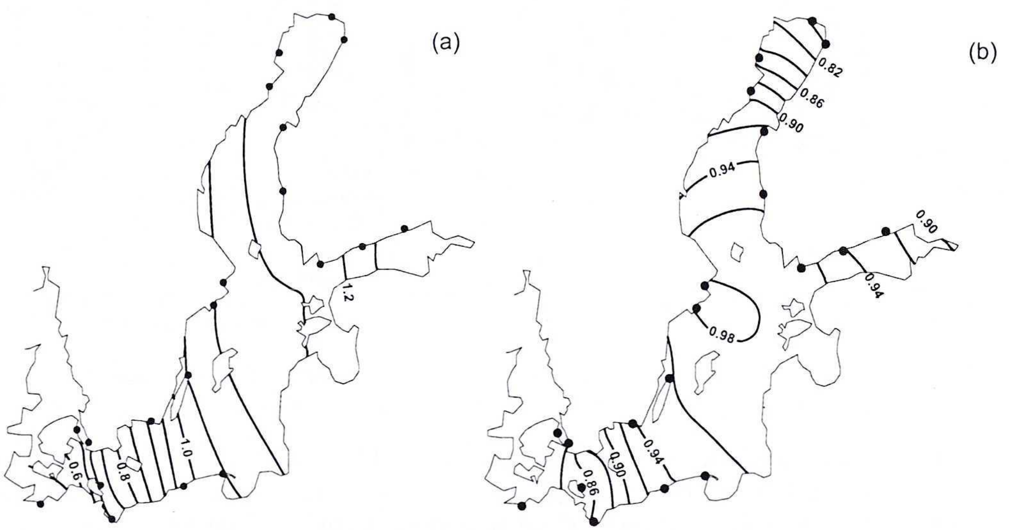

Fig. 2. 2D distribution of BSLM scale factor $\hat{H}(\varphi, \lambda)$ (a) (coefficient of regression of tidal records with the model time series) and its confidence level (b) (coefficient of correlation of tidal records with the model time series)

The map of a scale factor (Fig. 2a) exhibits a distinguished uniformity, smoothness and simplicity. Up to a decent approximation it could be expressed by a surface of parabolic cylinder with an axis pointing the NW-SE direction. The scale factor varies from 0.52 at Warnemünde to 1.17 at Kemi and 1.30 at Hamina. In the area where the regression coefficient exceeds 1 the variations of sea level are larger than those represented by the model. In particular, in the Bothnia Bay, sea level varies in a uniform way while there is a distinguished variation rate in south-western Baltic (Fig. 2a and Fig. 3a). Distribution of correlation coefficient (Fig. 2b and Fig. 3b) that vary from 0.78 at Kemi and 0.83 at Kobenhavn up to 0.98 at Stockholm and Landsort shows that the BSLM fits well to data records. It should be noted that the regular pattern of correlation coefficient distribution corresponds to the shape of Baltic Sea. The model fits best (largest correlation coefficient) to the actual sea level variations in the central part of the Baltic Sea around the parallel of Stockholm. Distribution of BSLM scale factor obtained fits well in coastal regions to sea surface topography computed from the Baltic Sea Level 1997 campaign as well as ERS-2 altimetry data of the year 1997 (Poutannen and Kakkuri, 2000).

Three different slopes of scale factor over Baltic indicate the existence of three distinguished, geographically associated groups of sites (Fig. 2a and Fig. 3a). One group consists of northern and middle Baltic sites down to Olands while to the second group belong the majority of southern Baltic sites; the third group contains tide gauges along Stockholm-Helsinki axis. Data records from Warnemünde and Swinoujscie tide gauges, probably due to their site-specifics as well as the location in rather turbulent sea region, do not fully follow the correlation pattern characteristic for the rest of the sea. This statement is consistent with the one pointed in (Wróblewski, 2001) and related to Swinoujscie tide gauge data.

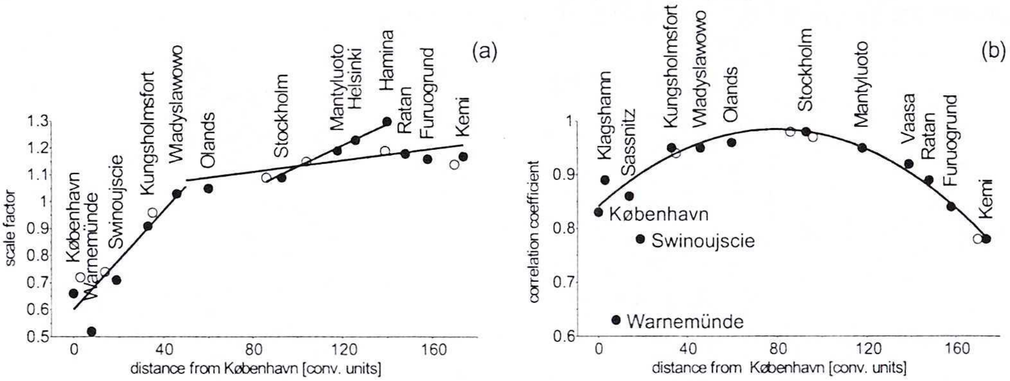

Fig. 3. Regression and correlation coefficients of tidal records with respect to the model time series vs. distance from København along Baltic Sea central waterline profile

The results of regression and correlation analysis of BSLM show that the model derived represents very well both global and regional features of Baltic Sea level variations. The BSLM can thus be used as reference to investigate local features of tide gauge records that reflect site-specific variations of sea level. The model can also be used for interpolating to fill the gaps in tidal records like it was done in case of Stockholm tide gauge record (Ekman, 2002). The BSML becomes a powerful tool for estimating the rate of trend of sea level variations that contain land uplift component. With use of BSLM the sea level at a site can efficiently be determined from data records of 10 years or even shorter (Krynski et al., 2004). It should be noted, however that even with a well-determined BSML the estimation of rate of trend of sea level variations using short tide gauge records is strongly biased. The BSML cannot be considered stationary on very short timescales.

4. Land uplift in Baltic region using BSML

Analysis of BSLM in both time and frequency domains showed that on timescales from ten years to a hundred years the model behaves as a noise-like process, stationary in terms of the mathematical expectation of mean value (Krynski et al., 2004). Subtraction of the model from initial data should not affect parameters of linear trend estimated from the residual time series. 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 (Krynski et al., 2004). Removing the BSLM from the time series of individual tide gauge makes it possible to estimate the rate of trend with substantially smaller errors.

In the numerical example shown in Fig. 4 a land uplift was estimated at the marked with black dots sites that consitst of all 15 sites contributing to BSLM as well as of a number of other tide gauges. The assumption of linearity of trend in the residual tide gauge record (time series obtained by removing the BSML from tide gauge record) was used. Each residual tide record was approximated using least squares with a linear function and then a rate of trend was determined. The contour lines in Fig. 4 were obtained by simple interpolation.

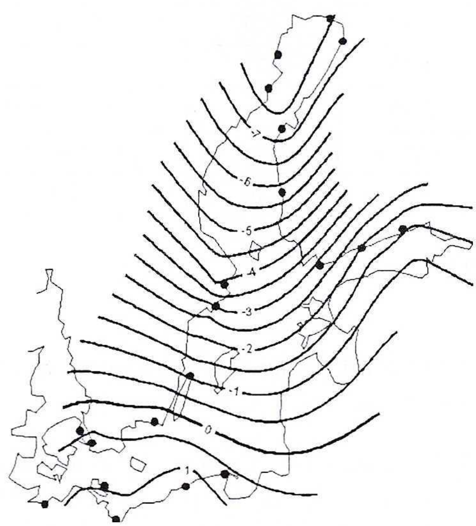

Fig. 4. Land uplift rates [mm/year] derived from tide gauge records with use of BSLM

It should be noted that the trend at some sites investigated exhibited distinguished non-linearity. The use of BSML seem suitable to study non-linear components of land uplift as well as to increase reliability of sea level and land uplift determination from short tide gauge data records.

The results of numerical experiments conducted are consistent with those in literature (e.g. Ollikainen et al., 2003) in terms of values of land uplift rates and the shape of their contour lines. Contour lines along the coast of Finland (Fig. 4) are very close to those for vertical rebound rates relative to mean sea level obtained from three precise levelling campaigns and the tide gauge in Hanko as well as for vertical rebound rates from GPS time series (Mäkinen, 2000; Mäkinen et al., 2001). Examples of uplift estimated using BSLM compared with literature data are shown below in Table 1.

Table 1. Determination of trend and comparison with literature data

tide gauge	rate of trend (*estimated*) [mm/year]	rms of rate (*estimated*) [mm/year]	rate of trend (*literature data*) [mm/year]	rms of rate (*literature data*) [mm/year]
Helsinki	-1.72	0.10	-2.16* -2.49**	0.08* 0.17**
Stokholm	-3.96	0.05	-3.89**	0.17**
Swinoujscie	1.07	0.14	0.82**	0.06**
Wladyslawowo	1.95	0.10	2.28**	0.65**
Warnemünde	1.07	0.15	1.17**	0.08**
Hamina	-1.25	0.14	-1.67*	0.07*
Hanko	-2.75	0.09	-2.75* -2.74**	0.07* 0.21**
Kungsholmsfort	0.25	0.07	-0.09**	0.14**
Oulu	-6.82	0.22	-6.92*	0.10*
Kemi	-7.17	0.23	-7.36* -7.28**	0.11* 0.39**
Mantyluoto	-5.73	0.10	-6.33*	0.02*
Vaasa	-7.18	0.14	-7.67* -7.30**	0.04* 0.17**
Ratan	-7.80	0.16	-7.83** -8.35***	0.20** 0.06***
Ustka	1.25	0.10	1.63**	0.59**

* (Vermeer et al., 1989)
** (Wöppelmann et al., 2000)
*** (Scherneck et al., 1998)

5. Variations of Baltic Sea level versus Earth rotation. Some properties of BSLM in time and frequency domain

Long time series of BSLM based on data records from about 200 years has allowed for conducting spectral analysis in a wide range of periods and for ensuring the steady spectral estimations of seasonal components. Noise-like spectral background of Baltic Sea level variations was discussed in (Vermeer et al., 1989; Krynski et al., 2004). Spectral analysis in the annual band shows the presence of three distinct seasonal components of annual, semi-annual and Chandler periods (Fig. 5a). The last component, the so-called polar tide, corresponds to the Chandler wobble period and is caused by the polar motion. The estimated amplitudes of those components are 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). Spectrum plot for the dispersion of estimated amplitudes shown in Fig. 5b corresponds to the spectrum plot of the amplitude as it is in agreement with the classical properties of Fourier's periodograms (the variance is proportional to the square of power density) (e.g. Anderson, 1971). To test the existence of terms with Chandler-like period in the periodogram of sea level variations the numerical experiment was performed. In the experiment seasonal variations of sea level were simulated on the basis of the sum of annual sinusoid with a signal with distingushed Chandler terms obtained from the component of polar motion.

An interpolated and smoothed fragment of periodogram of pole co-ordinates variations as well as rms of estimated amplitudes are shown in Fig. 5a and Fig. 5b, respectively.

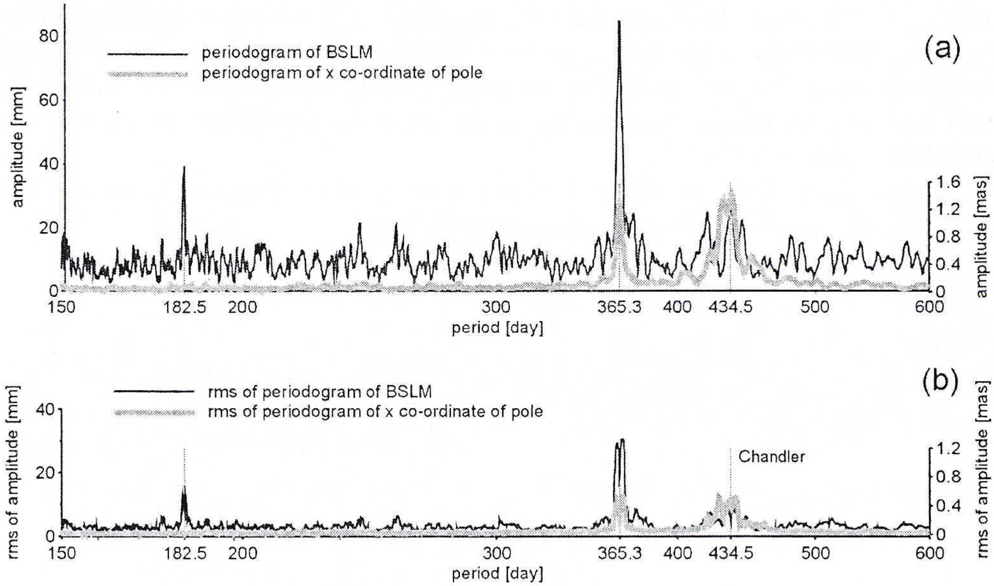

Fig. 5. Periodograms of variations of the Baltic Sea level and of variations of x-co-ordinate of pole (a) and rms of their estimated amplitudes (b)

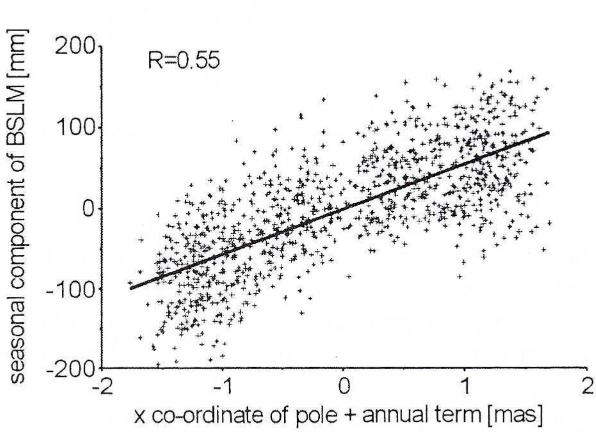

Fig. 6. Baltic Sea level variations in annual band vs. variations of sum of polar motion component and annual term with 1.2 mas amplitude

In the seasonal bandwidth of sea level variations and polar motion the same components are present. In particular a distinguished term of annual period as well as terms within Chandler frequency band occur in both spectra. They differ, however in terms of amplitude ratio. Similarity of sea level variations and polar motion spectra (Fig. 5) suggests a possibility of modelling sea level variations in terms of beat of annual and Chandler terms (Wiśniewski, 1978). In numerical experiment the simulated model (SM) consisting of annual sinusoid and component of the polar motion was compared with sea level variations (without annual sinusoid the signal of polar motion is very weakly correlated with sea level variations). The amplitude of added annual signal was scaled to make simulated model similar to BSLM in frequency domain in the seasonal bandwidth. Polar motion component used was the projection of polar motion vector onto the Baltic Sea mean meridian. Correlation between the simulated model and BSML in the seasonal bandwidth is shown in Fig.6.

Qualitative similarity of sea level variation series in the seasonal bandwidth and simulated polar-motion-derived model is shown in Fig. 7.

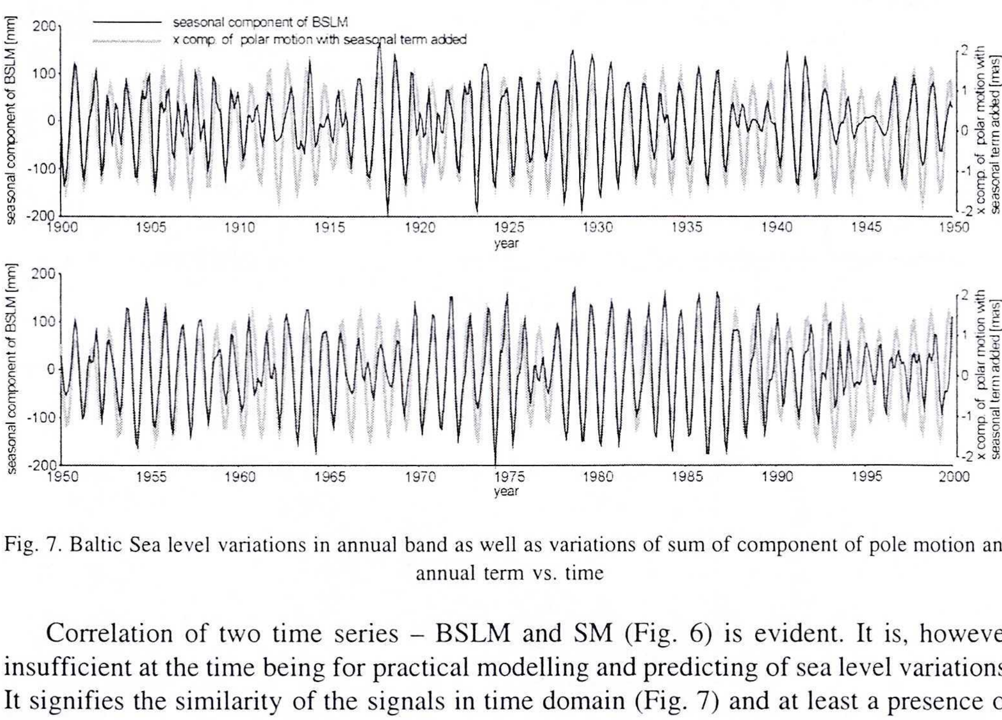

Fig. 7. Baltic Sea level variations in annual band as well as variations of sum of component of pole motion and annual term vs. time

Correlation of two time series – BSLM and SM (Fig. 6) is evident. It is, however insufficient at the time being for practical modelling and predicting of sea level variations. It signifies the similarity of the signals in time domain (Fig. 7) and at least a presence of common source of two different geophysical phenomena. Closer relationship of Baltic Sea level variations with polar motion could hopefully be determined in the course of further investigations.

Estimations of a rate of trend as well as a mean sea level are strongly affected by the large irregular-like disturbances observed in sea level variations. Those disturbances affect also the estimation of amplitudes of annual and Chandler band terms in BSLM what causes substantial difficulties in using polar motion data for modelling those variations. Such irregularities in sea level records were addressed in some publications (e.g. Bogdanov et al., 1994). It has been stated that due to the presence of such disturbances of sea level with alternating signs there exist periods when data provided is particularly favorable for geodynamics research. Results of the present study are in agreement with the mentioned statement. Similar irregular-like disturbances were observed in high resolution time series of GPS solutions (Krynski and Zanimonskiy, 2003). It has been shown that the use of empirical model leads to substantial reduction of irregular effects. The problem of disturbances as well as the presence of terms of decadal periods in variations of sea level make impossible today to estimate for the arbitrary epoch the rate of trend of sea level with accuracy of 10 mm/y from the tide gauge records shorter then tens of years.

Conclusions

Time series from all Baltic tide gauges examined exhibit a distinguished similarity. Common features of the records from tide gauges in Baltic Sea basin were used to generate the empirical model of Baltic Sea level (BSLM) variations by averaging tidal records from different sites. The model was considered as representation of temporal variation of Baltic Sea level with time-independent spatial distribution of its scale factor. The results of regression and correlation analysis of BSLM show that the model derived represents very well both global and regional features of Baltic Sea level variations.

The existence of three distinguished, geographically associated groups of sites that exhibit similar characteristics of tidal records-derived sea level variation was observed. One group consists of northern and middle Baltic sites from northern coast of the Bothnia Bay down to Olands. In that region sea level varies in the uniform way. To the second group belong the majority of southern Baltic sites. Tidal records in the southern region indicate smaller sea level variations that grow easterly. The third group contains tide gauges along Stockholm-Helsinki axis.

The BSLM is also useful as reference to investigate local features of tide gauge records that reflect site-specific variations of sea level. Data records from Warnemünde and Swinoujscie tide gauges, probably due to their site specifics as well as the location in rather turbulent sea region, do not fully follow the correlation pattern characteristic for the rest of the sea.

The BSML is found suitable for estimating a rate of trend of sea level variations that contain land uplift component. Removing the BSLM from the time series of individual tide gauge makes possible to estimate the rate of trend with substantially smaller errors. The use of BSML seem also suitable to study non-linear components of land uplift as well as to increase reliability of sea level and land uplift determination from short tide gauge data records. With use of BSLM the sea level at a site can efficiently be determined from data records of 10 years or even shorter. Thus the relatively short tide gauge data records can possibly be used in research on Baltic Sea level variability and kinematics of land uplift in the region using BSLM.

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. The uncertainty of rate of change of mean sea level determined from satellite data reaches 1.5-2 mm/year. Accuracy and temporal resolution of mean sea level determined from tide gauge records with use of BSLM seem reaching those obtained using satellite data.

Spectral analysis of the model of Baltic Sea level variations indicates the existence of distinguished term of Chandler period besides two major terms of annual and semi-annual periods. The existence of polar motion component in Baltic Sea level variations indicates a common source of those two different geophysical phenomena. Large irregular-like disturbances observed in sea level variations strongly affect the estimations of rate of trend as well as the mean sea level and cause substantial difficulties in using polar motion data for modelling those variations. There exist, however periods when tide gauge data provided is particularly favorable for geodynamics research. Such irregular effects can substantially be reduced when using an empirical model of sea level variations. Modelling and predicting Baltic Sea level variations with use of polar motion data might be possible in future but it needs an extensive research.

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Geodynamiczne aspekty zmian poziomu Morza Bałtyckiego określonych w oparciu o dane mareograficzne

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Streszczenie

Monitorowanie poziomu morza w oparciu o dane mareograficzne jest istotnym elementem badań geodezyjnych, geodynamicznych i oceanograficznych. Dostarcza ono informacji wykorzystywanych do określania poziomu odniesienia systemów wysokościowych, modelowania geoidy w obszarach nadmorskich, badania ruchów skorupy ziemskiej oraz badania dynamiki oceanów. Badanie zmian poziomu Morza Bałtyckiego stanowi ważny element studiów geodynamicznych na obszarze Centralnej i Północnej Europy. W ramach projektu badawczego, dotyczącego wyznaczenia centymetrowej geoidy na obszarze Polski, przeprowadzono analizę ciągów czasowych obserwacji mareograficznych ze stacji w basenie Morza Bałtyckiego. W oparciu o wspólne cechy zaobserwowane w ciągach czasowych z różnych stacji mareograficznych opracowany został model zmienności poziomu Morza

Bałtyckiego. O poprawności opracowanego modelu świadczy wysoki stopień jego skorelowania z danymi mareograficznymi z poszczególnych stacji. Regionalne charakterystyki modelu badano przy użyciu metod regresji i analizy korelacyjnej. Pokazano, że model odzwierciedla zarówno globalne jak i lokalne cechy zmienności poziomu Morza Bałtyckiego. Dyskutowane były również możliwości użycia opracowanego modelu jako odniesienia do badania w mareograficznych ciągach czasowych lokalnych cech, które odzwierciedlają specyficzne dla konkretnej stacji zmiany poziomu morza. Z analizy spektralnej modelu zmienności poziomu Morza Bałtyckiego wynika, iż w zmiennościach tych, obok zasadniczych wyrazów okresowych o okresach rocznym i półrocznym, występuje wyraźny wyraz o okresie Chandlera. Obecność w zmienności poziomu Morza Bałtyckiego składowej charakterystycznej dla nutacji swobodnej była badana przy użyciu analizy korelacyjnej. Na podstawie danych mareograficznych ze stacji z basenu Morza Bałtyckiego wyznaczono również parametry pionowego ruchu kontynentalnego, które są zgodne z odpowiednimi parametrami dostępnymi w literaturze.