The observation of seiches in the Baltic Sea using a multi data set of water levels

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Abstract

This investigation addresses the difficult problem of using a multi data set of water levels to study seich oscillations in the Baltic Sea. The Baltic Sea is a semi-enclosed sea area and is connected with the North Atlantic Ocean through the North Sea. The applied method is based on the analysis of environmentally corrected radar altimeter (RA) data in conjunction with simulated water levels obtained by an operational circulation model of the Federal Maritime and Hydrographic Agency (Bundesamt für Seeschiffahrt und Hydrographie, BSH) and tide gauge data. RA data of the First European Remote Sensing Satellite (ERS-1) have been analysed. The RA data were collected during the three-day repeat cycle from August 12 to December 9, 1991. An advantage of the analysis is the coverage and the geographical location of one and the same frequently repeated descending sub-satellite pass over the Bothnian Bay and the central Baltic Sea. Due to the assumed linear dynamics of this sea area the observation of sea level changes in the sense of a standing wave between the Bothnian Bay and the Baltic Proper is investigated. Amplitudes of water level changes up to 1 m have been recorded at tide gauge stations in the northern and southern parts of the Baltic Sea, respectively, during August and December 1991. Water level changes of less than 20 cm were calculated from the corrected altimeter data during the overflights of ERS-1. Tide gauge data and water level differences of tide gauge data measured at Kemi (Bothnian Bay), Finland, and Kolobrzeg at the Polish coast were used for frequency analyses. The analysed time series have been limited to five months due to the duration of the three-day repeat cycle of ERS-1. For frequency analysis the given sampling interval of 4 h is not appropriate, but a period of 12.4 h was clearly identified. This period corresponds to the fourth mode of theoretical estimated ones. The differences of water levels of the simulated data between Kemi and Kolobrzeg of about 25 cm agree fairly well with the results obtained by the RA data. Due to these results and the synoptic view of the along-track subsatellite passes it turned out that seiches can be observed by the ERS-1 radar altimeter. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: seiches; Baltic Sea; water level; radar altimeter; circulation model

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1. Introduction

Internal eigenoscillations and seiches in the Baltic Sea have been studied in great detail by Krauss (1963), and a brief overview is presented, for example, by Lisitzen (1974). The traditional theory of free oscillations in elongated basins is based on the channel hypothesis which was first applied to the Baltic Sea by Neumann (1941) and was further used by Krauss and Magaard (1962). Periods and structures of the gravitational free oscillations in the Baltic Sea were determined from theoretical calculations by Wübben and Krauss (1979).

A seich is a standing wave and can be observed due to water level changes using tide gauge data. Seiches in a partially enclosed water basin as the Baltic Sea have a natural period of free oscillation which depends on the shape of the basin and, hence, on the water depth and the number of nodes of the standing wave. In natural conditions, seiches are generated by air pressure gradients, wind effects, and co-oscillations with an adjoining water body. The excitation depends, as usually the case for forced oscillations, on the relation between the period of the excitation forces and the eigenoscillations of the ocean basin. As a consequence, floodings of coastal areas can arise through resonant effects. Seiches are also well known in other sea areas, for example, in the Adriatic Sea of the Mediterranean Sea Polli, . . . (1961) and the Caspian Sea Levyant et al., 1994.

The radar altimeter is a good complementing tool for measuring water levels due to its improving accuracy Shum et al., 1995. The knowledge of the existence of seiches between the Bothnian Bay and the southern Baltic Sea and the position of the descending subsatellite pass of the First European Remote Sensing Satellite (ERS-1) during the three-day repeat cycle were encouraging this investigation. Seiches can be observed either at least at two single locations for a certain period or, as a quasi synoptic view, along observation passes. Using a multi data set of sea surface heights, the system Baltic Proper–Gulf of Bothnia will be presented. The seiches between the Finnish Bight and the Baltic Proper have not been investigated here.

The oscillation period of the system Baltic Proper–Gulf of Bothnia computed by Neumann (1941) amounted to 39.1 h. Krauss and Magaard (1962) obtained the following periods for the oscillating water body extending from the city of Lübeck, Germany, in the southwest part of the Baltic Sea to the innermost parts of the Gulf of Bothnia: \( T_1 = 39.4 \) h, \( T_2 = 22.5 \) h, \( T_3 = 17.9 \) h, \( T_4 = 12.9 \) h, \( T_5 = 9.4 \) h, \( T_6 = 7.3 \) h, and \( T_7 = 6.9 \) h.

The bathymetry and geophysical peculiarities, tide gauge data, simulated water levels, and ERS-1 radar altimeter data are presented in Section 2. In Section 3 the meteorological data are described. The results are given in Section 4. Finally, Section 5 contains the conclusions.

2. The data

For the analysis of water level changes three independent data sets have been investigated. First, the occurrence and the frequency of the phenomenon have to be observed. Therefore, Finnish tide gauge data of Kemi at the Bothnian Bay and Polish tide gauge data of Kolobrzeg at the coast of the southern Baltic Sea have been analysed. These two tide gauge stations were selected, because they are situated nearby of the ERS-1 pass. The second data set being used are ERS-1 RA measurements. The advantage of RA data acquired by satellites is the quasi-synoptic two-dimensional registration of instantaneous water levels. Although the raw altimeter data have been preprocessed by the French Processing and Archiving Facility (F-PAF; CERSAT, 1994) there are still uncertainties about the accuracy of some correction parameters, for example, the geoid, the orbit, and the ionospheric correction. Therefore, the analysis of a third data set of simulated water levels obtained with a circulation model of the Federal Maritime and Hydrographic Agency (Bundesamt für Seeschifffahrt und Hydrographie, BSH), coinciding with the altimeter data, have been performed. The accuracy of the simulated water elevations has been verified using the data of 10 selected tide gauge stations around the Baltic Sea. The overall root mean square (RMS) difference was about 11 cm. Despite the unknown accuracy of the tide gauge data itself, they are the link to the other two data sets. The concept of the analysis is presented in Fig. 1. In fact, the proposed strategy by Marshall (1985) is faced from the
oceanographic point of view instead of the geodetic one. Using water levels from a well adapted regional ocean circulation model enables the discrimination between geoid errors and instantaneous sea surface heights. The analysis of small scale features using RA data in conjunction with the ocean circulation model has been performed to determine the fine structure of the geoid.

The use of along-track RA data of ERS-1 during the three-day repeat cycle has the great advantage that no interpolation in time is necessary for the investigation of seiches between the Bothnian Bay and the southern Baltic Sea. The 27 repeats reveal not only systematic errors in the RA data, like the geoid, but also oceanographic phenomena.

2.1. Bathymetry and geophysical peculiarities

The Baltic Sea is surrounded by nine nations: Finland, Russia, Esthonia, Latvia, Lithuania, Poland, Germany, Denmark, and Sweden. It is a semi-enclosed sea area which has a connection to the North Atlantic Ocean through the Kattegat and Skagerrak and the North Sea. The geographical extension is from 53°N–67°N and 10°E–30°E. The mean depth is about 55 m and the maximum depth of 459 m was measured in the Landsort Deep (Dietrich and Köster, 1974). The study area is characterized by a sequence of deep sea basins which are separated by submarine sills as shown in Fig. 2. A detailed description of the sea bottom topography and physical features of the Baltic Sea is presented by Mälkki and Tamsalu (1985). The bathymetry and the geometry of the basins have an important influence on the occurrence and periods of seiches in the Baltic Sea.

Due to the location in mid latitudes, the sea area is dominated by easterly and south-westerly winds. Parts of the Baltic Sea are ice-covered four to six months per season. The first ice period in 1991 was between November 16 and 23 (BSH, 1991). During this time only a small belt with thin ice was formed.
along the coast in the Bothnian Bay. The second ice period started on December 5, 1991. Due to the mild climate, the ice coverage was four to five weeks later than usual.

The land uplifting due to melting of the Scandinavian ice cap during the end of the last glacial period also has to be mentioned (Vermeer et al., 1988). This has to be considered when interpreting sea surface heights especially of the Baltic Sea. In addition, the different national height systems have to be taken into account very carefully when studying water levels (Ekman and Mäkinen, 1995). Another aspect
Fig. 3. The Baltic Sea with the location of the descending subsatellite pass of ERS-1 during the three-day repeat cycle and the positions of the analysed tide gauge stations.
Fig. 4. Time series of water levels for the tide gauge stations of Kemi and Kolobrzeg, respectively, during August 1 and December 31, 1991. The sampling interval is 4 h. The times of the selected along-track ERS-1 RA data are marked by arrows.

Fig. 5. Water level differences between Kemi and Kolobrzeg during August 1 and December 31, 1991. The times of the selected along-track ERS-1 RA data are marked by arrows.
when modelling the ocean dynamics of the Baltic Sea is the amount of river run off entering the sea area.

2.2. Tide gauge data

An overview of the geographical location of the descending subsatellite track of ERS-1 and the geographical positions of the analysed tide gauge data are shown in Fig. 3.

The sampling interval of the station of Kolobrzeg is 4 h. For quantitative estimations, the same time interval is needed for the station of Kemi which originally has a sampling interval of 1 h. Time series of water elevations of the tide gauge stations of Kemi and Kolobrzeg, respectively, between August 1 and December 31, 1991, are presented in Fig. 4. Three arrows indicate the times of the selected along-track ERS-1 RA measurements at 6274, 6490, and 7858 julian hours.

Fig. 6. Normalized autocorrelation function for the tide gauge station (a) Kemi and (b) Kolobrzeg during August 1 and December 31, 1991. The sampling interval is 4 h.
The water levels generally show variations within ±30 cm. During extreme meteorological events the water levels vary between ±1.2 m. It is evident that the two water levels are more or less in antiphase (see Fig. 4).

The time series of water level differences between Kemi and Kolobrzeg (\( \xi_{\text{Kemi}} - \xi_{\text{Kolo}} \)), which are characterized by high amplitudes at the station of Kemi, are shown in Fig. 5. The water level differences are about ±50 cm.

Because of the comparison of tide gauge data of Kemi and Kolobrzeg the minimum common sampling interval of 4 h was selected. With respect to the observation period from August to December the time series with 918 data points and 3668 h are too short for a detailed spectral analysis. Nevertheless, the obtained results look quite interesting. Bohle-Carbonell (1992) investigated different sampling intervals and resulting biased frequencies for observations of the North Sea. He concluded that it is very difficult to find the right sampling interval and data analysis method for the exact quantitative description of the interesting oceanographic phenomena.

The normalized autocorrelation function for the station of Kemi is shown in Fig. 6a. The maxima at about ±1000 h or 42 days are double-peaked. Superimposed is a period of 236 h which corresponds to about 10 days. The normalized autocorrelation function of the tide gauge station of Kolobrzeg is presented in Fig. 6b. This curve shows periods of 487 h, 968 h, 1513 h, and 2136 h which correspond to about 20 days, 40.3 days, 63 days, and 89 days, respectively. Superimposed is a period of about 128 h or 5.3 days. At the station of Kolobrzeg four oscillations within 2000 h have been found whereas at Kemi only two oscillations can be observed. Although the correlations are not very high, the long periods could be significant, whereas the superimposed small periods could be due to noise.

The spectral power density obtained from three different tide gauge data sets is shown in Fig. 7. The original sampling intervals of 1 h for the stations of Kemi and Kolobrzeg were used. Additionally, the Finnish tide gauge data of the station of Degerby which have been obtained during 3 years between 1991 and 1993 are also shown. The frequency of

![POWER SPECTRA FROM TIDE GAUGE DATA](image)

Fig. 7. Spectral power density of the original tide gauge data of Kemi, Degerby and Kolobrzeg. The frequencies of \( f = 0.081 \) h\(^{-1}\) (cph = 12.4 h) and \( f = 0.042 \) h\(^{-1}\) (cph = 23.9 h) are marked by arrows.
Fig. 8. Results of the (a) coherence, (b) admittance and (c) phase of tide gauge data from cross-correlation of Kemi and Kolobrzeg.
\[ f = 0.081 \text{ h}^{-1} \] which corresponds to the period of about 12.4 h is obvious in all three data sets, disregarding the different sampling intervals. Because of the reduced spectral power density of the Kemi data with respect to the Kolobrzeg data, this maximum can also be interpreted as the aliased frequency of the M₂ tidal constituent. It also corresponds with the fourth mode of \( T_2 = 12.9 \) h determined by Krauss and Magaard (1962). Another peak which is not well pronounced is close to the frequency of \( f = 0.042 \) h\(^{-1} \) which corresponds to 23.9 h and could be \( T_2 = 22.5 \) h (Krauss and Magaard, 1962). The periods longer than 1000 h which are shown in the normalized autocorrelation function in Fig. 6 cannot be identified in Fig. 7 due to the restrictions of the spectral analysis, e.g., the length of the time series.

The results of cross-spectral analyses of Kemi and Kolobrzeg are presented in Fig. 8a–c. It seems that the low-frequency parts of the spectral functions are strongly determined by atmospheric processes.

The coherence function (Fig. 8a) shows a prominent maximum with a period of 6.3 days corresponding to 127.2 h, and is certainly related to the natural meteorological cycle of atmospheric influences. The same period is determined by the normalized autocorrelation function of Kolobrzeg (see Fig. 6b). A second maximum at 2.4 days or 57.6 h corresponds apparently to the wind forcing or atmospheric pressure, possibly to storm surges. The narrow sharp maximum at a period of 12.4 h corresponds to the main tidal constituent M₂ or to the fourth mode of \( T_4 = 12.9 \) h.

The transfer function between the Kemi and Kolobrzeg data (Fig. 8b) for low frequencies \( \leq 0.02 \) h\(^{-1} \) or 0.4 cpd is very smooth and stable. The mean value is about 0.4. This means that oscillations in Kemi are 2.5 times stronger at these frequencies than in Kolobrzeg. On the contrary, the M₀ peak at 0.08 h\(^{-1} \) or 1.9 cpd, is three times stronger in Kolobrzeg than in Kemi (see Fig. 4).

The phase (Fig. 8c) for the same low frequencies as shown in Fig. 8b is very stable and close to 180°.

The same phase difference of 180° is observed also for a narrow frequency band at \( f = 0.08 \) h\(^{-1} \) which corresponds to 1.9 cpd.

### 2.3. Simulated water levels

The simulated water levels have been obtained with a three-dimensional circulation model operating at the BSH in Hamburg (Soetje and Brockmann, 1983; Metzner et al., 1995). The model is based on the so-called shallow water equations discretized with finite differences. It is an operational model to forecast water levels and currents for the North Sea and the Baltic Sea. The model is forced with 14 tidal constituents and with forecast winds and air pressure provided by the German Weather Service (Deutscher Wetterdienst, DWD) in Offenbach, Germany. The current model of the BSH is a predictive one, therefore, no analysed wind fields are used. For the calculation period of 1991, it was still a barotropic model version, but meanwhile it is a baroclinic one which also regards the ice dynamics. The model consists of three interactive nested grids with three different horizontal resolutions ranging from about 22 km in the coarse grid to 1.8 km in the finest grid. The flooding and drying of the Wadden Sea are also taken into consideration.

The evaluation of the accuracy of the simulated water levels is performed by using tide gauge data. Due to the model resolution the nearest grid cell with regard to the geographical location of Kemi, Degerby, Landsort and Kolobrzeg have been taken for verification. Time series of the simulated and measured sea surface elevations are shown in Fig. 9b–e.

Good qualitative agreement between each pair of the curves was obtained. During extreme water elevations, however, the simulated heights underestimate the observed heights. This could be due to the integrated effect of the box size, or due to the incorrectly predicted meteorological data of the DWD. Furthermore, a high frequency of water level changes is evident for the data of Kemi with regard
time series of water levels
sea area: Baltic Sea

- model data, — tide gauge data

3193; Kemi (ϕ: 65°40‘ N; λ: 24°32‘ E)

3165; Degerby (ϕ: 60° 1‘ N; λ: 20°23‘ E)

2073; Landsort (ϕ: 58°45‘ N; λ: 17°52‘ E)

115; Kolobrzeg (ϕ: 54° 6‘ N; λ: 15°19‘ E)

AUG SEP OCT 1991 NOV DEC
three hourly wind field data of the Baltic Sea
period: 01.08.-31.12.1991

864: Kami
\( \varphi: 65^\circ 42' \ N; \ \lambda: 24^\circ 30' \ E \)

100: Kolobrzeg
\( \varphi: 54^\circ 6' \ N; \ \lambda: 15^\circ 30' \ E \)

air pressure difference:
Kami (864) - Kolobrzeg (100)
to those of Kolobrzeg. This could be due to the geographical location of Kemi. The variation in air pressure which is of climatic origin and the surrounding of the Bothnian Bay by high mountains create a complex local atmospheric circulation causing local sea level changes.

One difficulty of the surrounding countries is the unification of the national levelling systems. The simulated data are calculated with regard to the Amsterdam zero level and, therefore, the water elevations for the North Sea and the Baltic Sea are related to this height system. Furthermore, the resulting height corrections for the simulated water levels probably reflect also the land uplift effect. For the stations Kolobrzeg at 54.1°N and Landsort at 58.7°N no height corrections of simulated data were necessary. However, for Degerby there should be a height correction of −12 cm and for Kemi of −2.7 cm, respectively. There exist not only a height difference in north–south direction of about 12 cm (Metzner et al., 1994), but also a height difference in west–east direction between Sweden and Finland has been observed. The overall RMS difference between the simulated and measured water levels for 10 selected tide gauge stations is 11 cm.

2.4. ERS-1 altimeter data

The analysed RA data have been sampled during the commissioning phase with a three-day repeat cycle between August 14 and December 9, 1991. During this period 44 overflights have been carried out, but due to data gaps only 27 passes of data were available. The descending subsatellite track took place at 1017 UTC during the time of about 200 s.

The equation for calculating altimetric sea surface heights after Cheney et al. (1987) has been slightly modified. First, the RA data have to pass selection criteria related to the quality of the signal.
criteria to avoid biases in the measurements. The
following limits have been especially determined for
the ERS-1 RA data and for the Baltic Sea: at least
five individual measurements must exist to account
for the $1\ s$ mean value; the standard deviation of the
altimetric height corrected for instrumental effects
must be in the range of $-1\ km$ to $0.6\ m$; the
electromagnetic bias must be smaller than $-0.04\ m$;
the significant wave height $H_{1/3}$ must be less than
$20\ m$ and the standard deviation of the averaged
backscatter coefficient must be in the range of $0\ dB$
to $0.4\ dB$. Since the circulation model is forced with
14 selected tidal constituents, the ocean tide correc-
tion was not applied to the altimetric signal. Due to
regional differences in the determination of the elec-
tromagnetic bias (Glazman et al., 1994) a polynomial
with a leading factor of $c = 0.02 \times H_{1/3}$ (CERSAT,
1994) was taken for the calculation of sea surface
heights.

One remaining uncertainty of ERS-1 RA data is
the accuracy of the orbit. To account for this error a
tilt and bias correction have been calculated for each
individual subsatellite pass and have been applied to
the individual data. A great advantage is the avail-
ability of simulated water levels when analysing
along-track RA data. After resampling the RA data
on a common grid with the simulated ones, the
residual orbit error was determined by minimizing
the height differences. The still remaining height
differences between the altimetric and the simulated
water levels at nearly the same geographical position
are due to the unknown local geoid undulations.

Based on the 27 repeated passes a mean profile of
geo id corrections was calculated. Following the sug-
gestions of Marshall (1985) the fine structure of the
marine geoid was superimposed to the given geoid
heights delivered with the geophysical data records
by the F-PAF. The geoid corrections ranging be-
tween $\pm 1.60\ m$, were also subtracted from the alti-
metric signal to calculate the final sea surface heights.

Because the simulated water levels have been
verified with tide gauge data (see Fig. 9b–e) the

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{image.png}
\caption{Quasi-synoptic along-track distributions of altimetric (crosses) and simulated (circles) water levels for (a) September 19, 1991, (b)
September 28, 1991, and (c) November 24, 1991. The regression line (dotted) and the connection of the first and the last simulated data
(straight line) are also shown; for geographical orientation of the descending pass four positions are marked at the upper $x$-axis.}
\end{figure}
b) water level in the Baltic Sea

result of the BSHs operational model: 28.09.91; 10:15:00

- after orbit and geoid correction -

\[ \begin{array}{cccc}
65^\circ 32' 49'' N & 62^\circ 41' 13'' N & 58^\circ 17' 51'' N & 54^\circ 11' 51'' N \\
23^\circ 3' 25'' E & 20^\circ 29' 18'' E & 17^\circ 20' 56'' E & 15^\circ 1' 11'' E \\
\end{array} \]

ERS-1 RA data (-16 cm), model data

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c) water level in the Baltic Sea

result of the BSHs operational model: 24.11.91; 10:15:00

- after orbit and geoid correction -

\[ \begin{array}{cccc}
64^\circ 25' 19'' N & 61^\circ 44' 49'' N & 57^\circ 35' 34'' N & 54^\circ 11' 31'' N \\
21^\circ 56' 45'' E & 19^\circ 42' 36'' E & 16^\circ 53' 13'' E & 14^\circ 59' 13'' E \\
\end{array} \]

ERS-1 RA data (-15 cm), model data

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Fig. 12 (continued).
accuracy of the further adjusted altimeter data is of the same order of magnitude as the model data (11 cm).

A comparison of RA data with tide gauge data was not carried out for the Baltic Sea. Such comparisons are normally performed with averaged RA data either for regions of 1° × 1° (Nerem et al., 1994) or over 25 km along-track segments (Mitchum, 1994). But this is physically senseless for the Baltic Sea. On the other hand, when studying the large scale ocean dynamics using environmentally corrected RA data the results are always related to mean sea surface heights which are then subtracted from the individual RA data (collinear analysis) or the classical crossover method was applied. These techniques have been published for example in the GEOSAT (JGR, 1990), and TOPEX/POSEIDON (JGR, 1994) Special Issues, and in the Proceedings of the ERS-1 Symposium 1 and 2 (ESA, 1993, 1994). Because of the not well known oceanic geoid undulations the altimetric sea surface heights are always calculated with regard to a given reference ellipsoid. Hence, the time series of sea surface heights are referenced to an arbitrary vertical point. In this study simulated time depending water levels are available and a direct comparison with quasi-synoptic altimetric sea surface heights is possible. Thus, the problem of the reference level has been avoided. For both data sets the Normaal Amsterdams Peil NAP; Waalewijn, 1987 in Amsterdam, the Netherlands was used. For comparison with tide gauge data, the height corrections for the national tide gauge stations with regard to NAP are also known (Metzner et al., 1994).

Therefore, a unique height system exists for the Baltic Sea and all three data sets can be compared.

3. Meteorological data

After analysing the sea surface height data of different data sources the question of the forcing arises. Because the circulation model is forced with meteorologically forecasted fields observation data of fixed weather stations have been analysed additionally. Data of 11 weather stations (Fig. 10a) were available, but first priority has been given to the stations of Kemi and Kolobrzeg. Two time series with a sampling interval of 3 h of recorded wind speed and direction as well as air pressure are shown in Fig. 10b–e. The wind field parameters are shown as vector diagrams (stick plots) in Fig. 10b and d.

At Kemi, the main wind direction was from south with varying wind speeds between 5 and 10 m/s during the analysed period and the air pressure varied between 971 and 1040 h Pa. The wind speed measured in Kolobrzeg varied only between 0 and 5 m/s. However, the main wind direction was also from south–southwest interrupted by short periods of northerly winds. The air pressure distribution of Kolobrzeg was comparable with the data of Kemi. The pressure field over the Baltic Sea shows a maximum variation of about 55 h Pa during the investigation period.

The air pressure differences between the stations of Kemi and Kolobrzeg are presented in Fig. 10f. The second half of September 1991 is characterized by air pressure differences of about 30 h Pa. During this period two overpasses of ERS-1 have been selected. During November 20–21, 1991 a more pronounced air pressure difference of about 40 h Pa was observed.

The time series of water levels recorded by the tide gauge station of Kemi and the air pressure variances of the weather station in Kemi are presented in Fig. 11. A standard air pressure of 1013 h Pa was subtracted from the individual data. High air pressure variances coincide with a decrease of the water level. It is assumed that these air pressure variances are probably responsible for the initialisation of standing waves like seiches.

4. Results

As an example, three along-track altimetric heights and the corresponding simulated water levels in the sense of a standing wave have been selected and are shown in Fig. 12a–c. The distribution of the simulated water levels is presented by crossed circles. The connection of the first and the last simulated water level is indicated by a straight line which underlines the assumed linear dynamics between the Bothnian Bay and the southern Baltic Sea. The tilting of the sea surface between the first and the last points gives a height difference of 25 cm. Ekman
and Mäkinen (1996) confirm this linear slope with their data. A linear regression curve has been calculated using the RA data (crosses) and is shown by the dotted line in Fig. 12a–c. Although a large scatter of the RA data was still remaining the same slope of the two different water levels was calculated.

On September 19, 1991, the slope of the sea surface has a positive value and the water level is decreasing towards the south of about 25 cm as shown in Fig. 12a. On September 28, 1991, the slope is reversed and shows a negative value. In addition, a superimposed wave is obvious in the simulated data presented in Fig. 12b. One reason could be a reflected wave caused by the narrows and low water depths in the northern part of the Baltic Sea at 60°N close to the Åland islands (see Fig. 2). Fig. 12c shows the situation for November 24, 1991, where the slope is again reversed compared to the case on September 28, 1991. The height difference between the ends of the along-track data is about 25 cm and is of the same order of magnitude as on September 19, 1991 (see Fig. 12a). These trends of water level changes are confirmed by tide gauge data shown in Fig. 4 and water level differences presented in Fig. 5.

The distribution of the RA data at the three selected times and the simulations carried out for September 28, 1991 show an oscillation close to the third mode with $T_s = 17.9$ h which has been calculated by Krauss and Magaard (1962). However, there is no indication for such an oscillation obtained by the results of the spectral analysis presented in Figs. 6–8. It has also to be mentioned that the simulated heights underestimate the observed heights by a factor of 0.5.

5. Conclusions

Three independent data sets of radar altimeter measurements, simulated water elevations, and tide gauge data have been investigated to study seich oscillations in the Baltic Sea. The RMS difference between the simulated and measured water levels of ten selected tide gauge stations around the Baltic Sea was 11 cm during August and December 1991. According to the applied method of comparing simulated and RA data, an increasing slope from south to north of the Baltic Sea was estimated. The water level differences between Kemi and Kolobrzeg of $\zeta_{\text{Kemi}} - \zeta_{\text{Kolo}} = 25$ cm were calculated and measured. This confirms that sea level changes in the sense of seiches can be observed by radar altimeter data. The linear assumption for the ocean dynamics is also supported by the results published by Ekman and Mäkinen (1996). The theoretical results obtained by Krauss and Magaard (1962) for the oscillation period of the system Baltic Proper–Gulf of Bothnia could not be confirmed exactly. The time series of about four months between August and December 1991 with a sampling interval of 4 h are not appropriate for spectral analyses. Only a period of 12.4 h was clearly identified in the power spectra of the analysed data. This peak corresponds to the $M_2$ tidal constituent and to the fourth mode of the oscillation period derived by Krauss and Magaard (1962). The air pressure variances seem to be the dominant forcing parameter for water level changes. In addition, the dominant wind direction from south–southwest is supporting oscillations like seiches, because the main axis of the Baltic Sea is in the same orientation.

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