Near-coastal satellite altimetry: Sea surface height variability in the North Sea – Baltic Sea area

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Abstract

The radiometer wet tropospheric correction is a limiting factor of the application of near-coastal altimetry observations in the North Sea – Baltic Sea area. Using an ECMWF model based correction instead, we increase the return rate from 70% to 95%, with observations as close as 10 km from the coast. The altimetry and 39 coastal tide gauges are referenced to the same state of the art regional geoid. The two datasets are highly correlated and reveal a consistent mean dynamic topography and two distinct correlation regimes separated by the Danish islands. The combination of the two datasets in a simple statistical model is shown to estimate the sea surface height with the same error level as state of the art operational models, indicating the potential for near-coastal applications of satellite altimetry observations.

1 Introduction

Prediction of the sea surface height (SSH) extremes, occurring in connection with storm surges, is important for people living in high risk storm surge areas, such as the North Sea – Baltic Sea area (Schmidt-Thomé, 2006). The risk of storm surges in the area is expected to increase with future climate change (Woth, Weisse, & Storch, 2006).

To predict storm surges, most countries in the area run operational water level prediction models (Flather, 2000). However, these models depend on weather forecasts, and have errors of 10–20 cm, with an extreme of 1 m (J. W. Nielsen, 2001)(recent validations available at ocean.dmi.dk). The use of satellite altimetry observations in this region is limited due to coastal effects and a discrepancy between the satellite repeat period and the time scale of the SSH variability. Høyer and Andersen (2003) showed that a statistical model, based on multivariate regression analysis of satellite altimetry and tide gauge data, can estimate the real-time sea surface height in the North Sea to within 10 cm's accuracy. In this study we recover satellite data as close as 10 km from the coast using an ECMWF based wet tropospheric correction and extend the statistical model to the coastal regions of the Inner Danish Waters (IDW) and the Baltic Sea. The TOPEX/Poseidon – Jason-1 tandem mission gives a high spatial resolution and demonstrates the potential of these data, even in coastal regions, and the use of an absolute reference frame allows for direct comparisons of altimetry, tide gauge, and model data.

2 Study Area

The North Sea is a semi-enclosed sea with a large open boundary to the North Atlantic (Figure 1). It is characterized by well-mapped tidal variations with amplitudes up to 5 meters (Andersen, 1999). The largest non-tidal variations are caused by atmospheric low pressure systems, either as external surges from the North Atlantic or internally generated surges (Heaps, 1983).

The Baltic Sea can be regarded as a large estuary, its only connection to the world ocean being through the IDW and the North Sea. The large river input and resulting salinity gradient creates a 35–40 cm mean sea surface topography difference between the northern Baltic Sea and the North Sea (Ekman & Mäkinen, 1996). In the Baltic Sea, the main SSH variations are of meteorological origin, with significant seasonal and interannual variations. The tides are only a few centimeters.

The flow through the IDW is governed by sea level differences between Skagerrak and the southwestern Baltic Sea and by hydrological control (M. H.

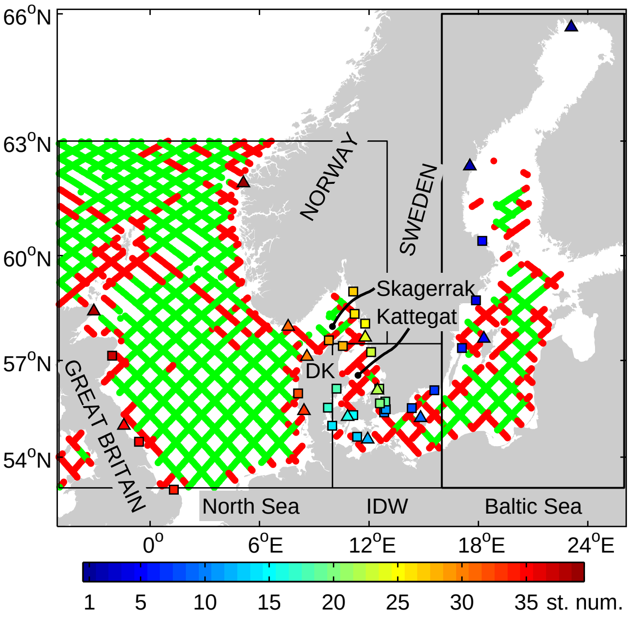

Figure 1: Study area. Dots mark satellite data, showing an example (Jason-1 cycle 37, TOPEX/Poseidon cycle 380, 7–17 January 2003) of the data availability with (green) and without (red) the radiometer land mask. Triangles mark tide gauges used for the statistical model, squares mark tide gauges used for validation. The color of triangles and squares indicates station numbering (st. num.) used in this paper. The outlines define the three sub-study areas as they are used in this paper, DK stands for Denmark.

Nielsen, 2001). This limits and delays the water exchange between the North Sea and the Baltic Sea, damping out signals with a time scale of less than a few days.

3 Data and Methods

Altimetry data from the TOPEX/Poseidon and Jason-1 satellites have been retrieved from the RADS database (Scharroo, 2005) to cover the North Sea – Baltic Sea area and the time period January 2002 to May 2005 (The tandem mission phase, Figure 1). Data from the calibration phase (January to August 2002) are used to check the near-coastal methods described below, later data (where the satellites flew side by side, doubling the spatial resolution) are used for the further analysis presented in this paper. Default settings in the RADS database as described by Scharroo (2005) are used, except for the use of ECMWF model based wet tropospheric correction and a change to EGM96 as reference surface. The reference surface is then changed to the GOCINA regional geoid (Knudsen et al., 2007). No data are removed because of radiometer or brightness temperature flags. To allow for comparison with tide gauge data, the inverse barometer correction is not applied.

The available tidal corrections in the database are not expected to be valid in these near-coastal regions (Andersen, 1999), and instead the result of a pointwise least square harmonic fitting of the significant tidal constituents (amplitude larger than 5 cm) is removed from the data set. In the North Sea, these are O_1, K_1, N_2, M_2, S_2, K_2, and M_4, in Skagerrak and Kattegat it is only M_2, and in the southern IDW and the Baltic Sea, the tidal signal is insignificant.

Tide gauge data from 39 Swedish, Danish, Norwegian, and British stations (Figure 1) are collected, checked for outliers, and corrected for tides using the same constituents as for the satellite data. A three hour mean value is used, it has shown to give the largest correlation with the satellite data. Information on the local datum of all stations is collected, and the reference level changed to the GOCINA geoid.

The correspondence between tide gauge and satellite data is checked by comparing the mean dynamic topography (MDT) at each tide gauge with that of satellite measurements within a fixed radius of the station (Figure 2), and by correlation analysis between the tide gauge and altimetry data time series in each satellite measuring point (Figure 3).

To combine the high spatial coverage of the satellite data with the hourly resolution of the tide gauge measurements, a statistical model based on multivariate regression analysis is set up (Høyer & Andersen, 2003; Emery &

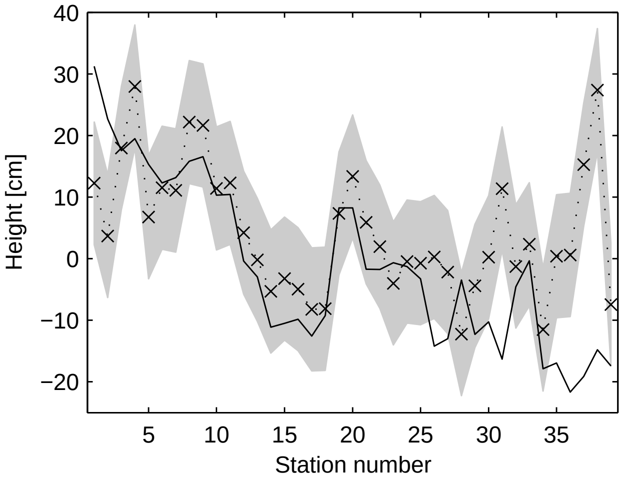

Figure 2: Mean dynamic topography relative to the GOCINA geoid; dotted line with crosses show tide gauge data and shaded area indicates geoid uncertainty; solid line show mean satellite data within 75 km of each station.

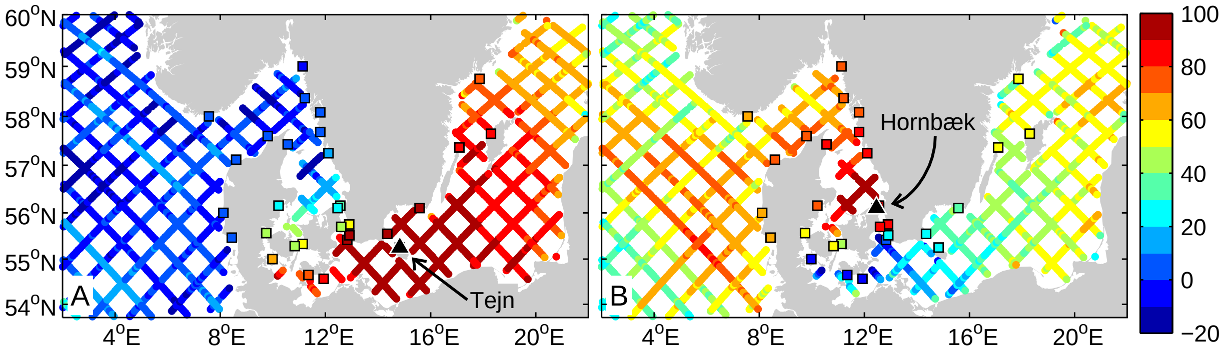

Figure 3: Correlation [%] between selected tide gauge measurements (A: Tejn station, B: Hornbæk station) and altimetry measurements. The correlation with other tide gauge stations is also shown with colored squares at each station.

Thomson, 2001). This model calculates the best weighted sum (least squares sense) of data from a range of surrounding tide gauges and a constant offset, to fit the altimetry data time series in each satellite measuring point. 14 of the 39 tide gauges are used for the analysis; the stations are selected based on the correlation analysis to give a good coverage, and unused stations allow for evaluation of the method. Assuming that the statistical properties of the sea surface height field are constant in time, the statistical model can estimate the SSH at any satellite measuring point from the tide gauge measurements alone. This allows for real time prediction of SSH.

4 Results

The data availability of standard altimetry products is limited to approximately 50 km from the coast by the land mask of the on-board radiometer. The along-track altimetry footprint size is less than 15 km, depending on the wave height. By using the ECMWF wet tropospheric correction instead of the correction calculated from the on-board radiometer, we get data in the near-coastal zone and thereby increase the data availability in the study area from approximately 70% to approximately 95% (Figure 1). The ECMWF correction is used in the entire study area for consistency, and the increased error in the wet tropospheric correction is estimated to be 1 cm by root mean square (RMS) analysis.

The quality of the now recovered near-coastal altimetry measurements can be checked during the calibration tandem mission phase. During this phase, the two satellites measured along the same ground track with a 70 seconds separation. In the study area, there is a mean difference of 15.1 cm between the two altimeters' SSH measurements, in agreement with Fu (2004). The standard deviation of the differences is generally below 4 cm until 10–20 km from the coast. This is similar to the error budget of open ocean measurements, and indicates that the near-coastal altimetry measurements are of high quality.

Figure 2 shows the tide gauge MDT as well as altimetry MDT averaged within a 75 km radius of each tide gauge station. The 75 km are chosen to give the best fit, balancing altimetry data coverage and geographical variance. The high degree of agreement at Swedish and Danish stations indicates that the reference systems are consistent, and that satellite and tide gauge MDT measurements correspond well. The expected variation of the MDT out through the Baltic Sea to the North Sea is clearly seen for stations number 1–33. The differences between tide gauge and satellite data at the British North Sea coast (number 34–38) correspond to a tilt of the British reference system of about 6.4 cm/°N, agreeing within the error level with Thompson (1980).

The correlation between tide gauge data and nearby altimetry data is above 90% at all tide gauge stations, but the spatial correlation lengths vary through the study area. In the Baltic Sea, the correlation stays above 70% within 500–1000 km of the tide gauge stations; in the North Sea only within 200–300 km. The temporal correlation lengths show a similar pattern, with autocorrelation time scales at the tide gauges of 1–3 days in the North Sea and 1–2 weeks in the Baltic Sea. As shown in Figure 3, the change in correlation pattern is very abrupt and focused at the narrow straits of the IDW. Where the Tejn tide gauge has a high correlation with the southern Baltic Sea and the southern part of the IDW, but not with Kattegat and the North Sea, the image is reversed for the Hornbæk tide gauge, less than 200 km away.

The performance of the statistical model is evaluated by comparing the model results with the satellite data and data from tide gauges not used in the model. Evaluated against satellite data, the model RMS error is 6–12 cm in the North Sea, 4–8 cm in the IDW and 2–6 cm in the Baltic Sea. This includes all error sources, among these high frequency atmospheric effects. The error distribution is generally smooth, indicating acceptable tide gauge coverage. Exceptions of the good performance are in the eastern Baltic Sea, where the model would benefit from one or two additional tide gauges, and in the southern North Sea, where non-linear tides requires a more sophisticated tidal model. To compare with unused tide gauges, model points within 75 km of the station are averaged and used. Selected statistical results of the comparison are shown in Table 1. Here the peak error (PE) is defined as the mean amplitude underestimation of the ten highest water level events in a year. The PE is highly variable between stations and from year to year, but is positive everywhere, indicating a general underestimation of storm surge amplitudes. For three of the IDW stations, only data from one of the satellites are used, because data from the other satellite are more than 75 km away or in an unfavorable position, giving model to tide gauge correlations below 50%. Thus, the doubled spatial resolution of the tandem mission shows its importance. The Cromer tide gauge has been excluded; it is located in the southern North Sea where strong non-linear tidal effects makes this method unsuitable. The model performance in the North Sea is comparable to that of Høyer and Andersen (2003). In the IDW and the Baltic Sea, the model performs better than in the North Sea, showing a successful extension of the model to these near-coastal areas. The different statistical results of the Baltic Sea and the North Sea are most likely caused by the different correlation scales, and because high water signals in the North Sea travel as Kelvin waves with exponentially increasing water level towards the coast

Table 1: Mean RMS error [cm], correlation (cor.) [cm], and PE [cm] over the years 2003 and 2004 in the three sub-study areas when comparing the statistical model to tide gauges not used in the model.

	RMS	cor.	PE
Baltic Sea	4.7	98	11
IDW	8.6	91	10
North Sea	8.9	94	19

(e.g., Gill, 1982).

Modeling of the storm surge in the IDW on 1 November 2006 gives an example of the model performance. This was a 100 year event, causing extensive flooding and material damage. It was caused by an unusual wind pattern with northerly winds both in Kattegat and the Baltic Sea, the resulting high waters meeting in the IDW. As seen in Figure 4, the statistical model gives a qualitatively good estimate of the event, with a high correlation coefficient, but underestimates the amplitude with 22 cm on average.

The evaluation of the statistical model at independent tide gauges makes way for direct comparison of the error statistics with those obtained with the Danish Meteorological Institute (DMI) primitive equation operational storm surge model (ocean.dmi.dk). As seen in Figure 4A, the correlation of the statistical model is comparable to or better than that of the operational model, and the peak error is smaller than the operational model in the IDW (Figure 4B). For the test case of 1 November 2006 (Figure 4C), the peak error of the operational Mike 21 model is significantly higher than that of the statistical model. However, DMI is currently changing to storm surge predictions based on the BSH CMOD model, and the peak error of the new model is comparable to that of the statistical model.

5 Concluding Remarks

Satellite altimetry data are nowadays widely available in a ready-to-use form for the open ocean, but near-coastal applications require more specialized data treatment. Based upon the findings above, several conclusions are reached about the application of satellite altimetry observations to study SSH variations in the Baltic Sea, IDW, and North Sea.

The radiometer replacement is a simple but important method for retrieval of satellite altimetry data in near-coastal areas. It is seen that the

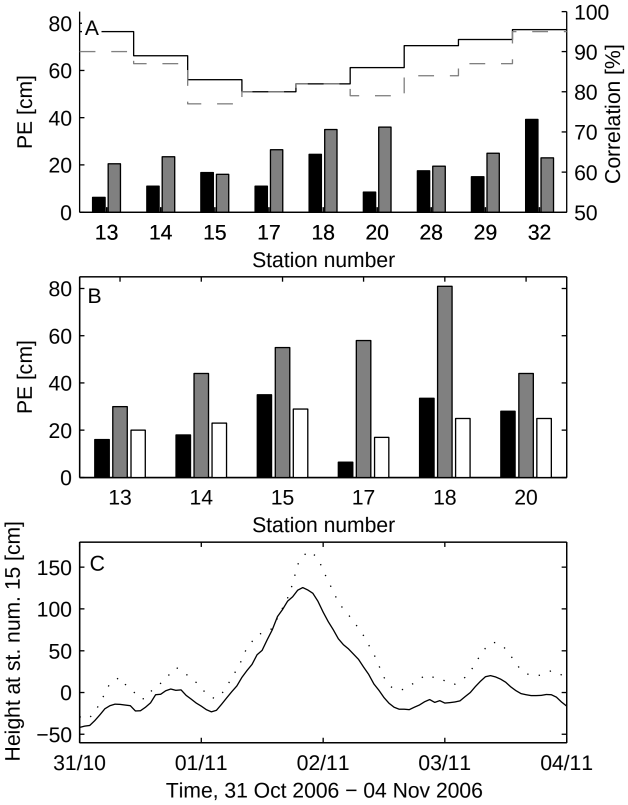

Figure 4: A: Mean PE (bars and left axis) and mean correlation (stair plot and right axis) of the statistical model (black, solid curve) and the Mike 21 model (gray, dashed curve) of Danish tide gauges not used in the statistical model. B: PE for the 1 November 2006 storm surge of the statistical model (black), Mike 21 (gray) and BSH CMOD (white) for those of the above stations located in the IDW. C: Example of the statistical model prediction at station number 15 (Korsør). Dotted curve shows the observations, solid curve shows the statistical model estimation.

recovered altimetry data are of high quality, but the alternative wet tropospheric correction has an increased error of about 1 cm. For storm surge modeling purposes the increased error is insignificant compared to surges of meters. For other purposes, interpolation of the valid radiometer wet tropospheric correction estimations is possible (Vignudelli et al., 2005). To obtain altimetric data even closer to the coast, retracking is necessary (e.g., Deng & Featherstone, 2006).

The coastal altimetry data, as well as tide gauge data, are referred to a regional geoid, showing the high degree of correspondence in both the relative variations and, for the Swedish and Danish tide gauges, the absolute level. The MDT pattern found here agrees well with Ekman and Mäkinen (1996). However, the quality of the MDT obtained this way depends strongly on the geoid model, and since state of the art geoid models for the study area have an uncertainty of 5–10 cm, detailed studies are not possible.

A simple statistical model for real-time estimation of the SSH in the North Sea – Baltic Sea area is shown to perform on the same level as state of the art operational storm surge models. However, it must be remembered that the operational models run forecasts (here 0–6 hours), while the statistical model is capable of real time estimation only. The statistical model should therefore be seen as a supplement to the primitive equation models, independent of weather forecasts. The comparable performance of the operational models and this very simple statistical model, and the high degree of correspondence in reference levels are indications that assimilation of tide gauge and altimetry data could improve the performance of the operational sea surface height prediction.

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