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for Multi-Decadal Regional Ocean Model  
Simulations for the North Sea**

**Authors:**

*T. Aspelien*

*R. Weisse*

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**Authors:**

*T. Aspelien*

*R. Weisse*

*(Institute for Coastal Research)*

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## Assimilation of Sea Level Observations for Multi-Decadal Regional Ocean Model Simulations for the North Sea

Trygve Aspelien and Ralf Weisse

*19 pages with 7 figures and 1 table*

### Abstract

A simple and cost-efficient nudging scheme suitable for multi-decadal integrations of regional ocean models was implemented into a regional ocean model for the North Sea. The scheme was tested for a 23-month period from January 2000 to November 2001. Compared to a control simulation that did not utilize any form of data assimilation the simulation of near coastal sea level elevations and storm surge variability improved considerably when the nudging scheme was applied. The improvement was found to be particularly large near the open boundary where reduced boundary effects may become important and near the German coast where external processes, not accounted for in a model run without data assimilation, may be relevant. Most of the improvement was obtained when data from a single tide gauge have been assimilated, while the assimilation of additional tide gauges yielded only marginal further improvements. It is suggested that the scheme may result in an improved representation of natural storm surge variability when applied to multi-decadal periods.

Assimilation der Meeresspiegel-Beobachtungen für regionale Ozean-Modell-Simulationen für die Nordsee über mehrere Jahrzehnte

### Zusammenfassung

Ein einfaches und kosteneffizientes Datenassimilationsverfahren wurde in ein regionales Ozeanmodell für die Nordsee implementiert. Das Verfahren basiert auf einem simplen Nudging-Ansatz und ist geeignet, solche Modelle bei vertretbaren Rechenzeiten über mehrere Jahrzehnte zu integrieren. Die Methode wurde anhand einer 23monatigen Simulationsperiode von Januar 2000 bis November 2001 getestet und die Modellergebnisse mit einer Kontrollsimulation ohne Datenassimilation verglichen. Im Vergleich zu dieser Simulation konnte eine erhebliche Verbesserung der simulierten Wasserstandsschwankungen erreicht werden. Die größten Verbesserungen konnten dabei an den offenen Modellrändern sowie in der Nähe der deutschen Küste erreicht werden. Es wird gezeigt, dass bereits die Assimilation einer einzelnen Pegelzeitreihe zu erheblichen Verbesserungen der Modellresultate führt, während die Hinzunahme zusätzlicher Pegeldaten nur geringfügig weitere Verbesserungen bringt. Die Ergebnisse legen nach, dass die Methode zu einer verbesserten Darstellung der natürlichen Variabilität in Langzeitsimulationen des regionalen Sturmflutklimas beitragen kann.



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# 1 Introduction

Regional multi-decadal ocean simulations have become more and more common in the recent past. One of the first 40-year simulations was described by *Flather et al.* [1998]. They forced a two-dimensional storm surge model covering the Northwest European continental shelf with meteorological data from the Norwegian Meteorological Institute for the period 1955–1994. Comparing observed and modeled data they concluded that realistic estimates of surge extremes could be derived directly from model simulations provided that the atmospheric forcing has sufficient quality. They suggested that such estimates could be made for areas (e.g., offshore) or situations (e.g., future climate) where no observational data exist. More recently, similar multi-decadal simulations utilizing different and/or improved meteorological forcings have been performed by e.g., *Langenberg et al.* [1999], *Kauker and Langenberg* [2000] or *Wakelin et al.* [2003].

The data obtained from such long-term simulations have been used extensively in recent years. Examples are the assessment of storm related long-term sea level variations (e.g., *Langenberg et al.* 1999), the description of natural ocean variability (e.g., *Kauker and Langenberg* 2000, *Meier and Kauker* 2003) or the regionalization of climate change (e.g., *Schrumm* 2001). Furthermore, in combination with climate change scenarios (e.g., *Flather and Smith* 1998, *Lowe et al.* 2001) the natural climate variability obtained from such simulations represents an essential backbone for climate change attribution and detection studies. Because of modeling constraints it remains, however, unlikely that the natural variability is fully captured by such simulations. The two main reasons comprise deficiencies that are inherent in every model simulation and physical aspects that are not adequately taken into account in the simulation. Examples are constraints caused by limited model domains or sub-grid scale physical processes that have to be parameterized in a more or less sophisticated way.

In a strategy paper addressing the coastal module of the global ocean observing system [*UNESCO*, 2003] it was suggested that for model hindcasts such shortcomings can be reduced when the simulations are effectively combined with existing observations. The intention of such model hindcasts is twofold: First, they provide information about variables that have either not been observed directly or that have been sampled only insufficiently in space and time, and second, they yield an improved representation of the observed natural variability. The techniques that effectively combine dynamical models with observational data are commonly referred to as data assimilation.

Presently a large variety of data assimilation techniques exist. They are extensively described in the literature, and overviews are given by, e.g. *Daley* [1991], *Anderson et al.* [1996] and *Brink and Robinson* [1998]. Generally, data assimilation techniques can be divided into two approaches: variational (adjoint) (e.g., *Lorenz* 1988, *Sasaki* 1970) and sequential methods (e.g., *Bertino et al.* 2003). Variational methods usually comprise the minimization of a cost function by various techniques. Sequential methods are for example the Kalman Filter (e.g., *Kalman* 1960, *Gelb* 1974, *Jazwinski* 1970), ensemble Kalman filters (e.g., *Evensen* 1994), Singular Evolutive Extended Kalman Filter (SEEK filter) (e.g., *Brasseur et al.* 1999), optimal interpolation (e.g., *Daley* 1991), successive correction (e.g., *Bratseth* 1986), or spectral nudging (e.g., *Waldron et al.* 1996, *von Storch et al.* 2000).

Most of these techniques have originally been developed and applied in atmospheric sciences. For ocean modeling, data assimilation represents a relatively new research area. According to *Brink and Robinson* [1998] earliest attempts date back to 1982, when *Bennett and McIntosh* [1982] used a weighted variational approach to include reliable sea level data from the coastline in combination with ad-hoc open boundary conditions. More recently, also more advanced techniques have been applied to ocean models, however, for relatively short periods of time only.

Presently, in oceanography most efforts are concentrating on the assimilation of sea level (e.g., *Zhang et al.* 2002, *Haugen and Evensen* 2002). So far, sea level represents one of the best and most frequently observed ocean variables from both, tide gauges and satellites. For tide-surge modeling, the accurate representation of its variations is of outstanding importance as the barotropic circulation is completely determined by spatial sea

level gradients. More recently, efforts have been made also to assimilate other variables such as temperature (e.g., *Keppenne and Rienecker 2003, Haugen and Evensen 2002*) or phytoplankton for eco-system modeling (e.g., *Johannesen et al. 1993, Allen et al. 2000*).

So far, all data assimilation efforts in ocean modeling have focused on the simulation of relatively short periods, up to a couple of years, concentrating mainly on the potential improvements (e.g., *Høyer and Andersen 2003*) or on the applicability for routine forecasts (e.g., *Cañizares et al. 2001*). Because of the extensive computer resources required by data assimilation schemes, to our knowledge no multi-decadal simulation utilizing any form of data assimilation has been performed up to now.

The objective of this paper is to implement and test a data assimilation scheme that can be applied for multi-decadal ocean simulations. Because of the large computing costs of such simulations and the restricted availability of observational data for long periods such a scheme should meet the following requirements:

1. It should be simple and cost efficient and
2. It should utilize only observational data
  - that are available on multi-decadal time scales
  - that have sufficient accuracy
  - that are sufficiently homogeneous on multi-decadal time scales, and
  - that are available at high spatial and temporal detail.

So far, sea level measurements from tide gauges represent one of the best possible choices to meet the second requirement. Satellite data are available only for periods that are still too short for multi-decadal simulations. In order to meet the first constraint, a simple nudging scheme, that requires only marginal extra computing costs, was adopted. The scheme is briefly described in Section 2. For this study it has been implemented into a regional ocean model set-up for the North Sea. The model and the model set-up are described in Section 3 together with our experiments, data and validation strategy. In Section 4 the results are presented. They are summarized and discussed in Section 5.

## 2 The Nudging Scheme

Generally nudging refers to a relaxation of the model towards a measured value. The relaxation may be combined with a linear interpolation using a weighting matrix based on an empirical weighting function. When only the sea level height  $e$  is assimilated, the relaxation can be expressed by

$$e^a = e^m + W(e^o - e^m) \quad (1)$$

where the superscripts  $a$ ,  $m$  and  $o$  refer to the analysis, the model and the observation, respectively.  $W$  represents an empirical weighting function defined by

$$W = \alpha \exp\left(-\frac{r^2}{2L^2}\right). \quad (2)$$

Here  $r$  measures the distance between the model grid point and the location of the observations, while  $L$  refers to a characteristic length scale within which observations will have a significant influence on the analyzed value  $e^a$ . The quality of the observations is taken into account by the empirical coefficient  $\alpha$  with  $\alpha = 1$  indicating perfect observations.

Equations (1) and (2) can formally be applied to all model grid points  $i = 1 \dots M$ . When, for a particular time, several measurements are available within the radius defined by the area of influence, weights are computed taking the  $N$  observations within this radius into account

$$e_i^a = e_i^m + \sum_{k=1}^N \frac{W_{ik}}{\sum_{j=1}^N W_{ij}} W_{ik} (e_k^o - e_i^m). \quad (3)$$

Compared with more advanced techniques this nudging scheme is rather simple. With respect to multi-decadal simulations it has, however, several advantages: It is cheap in terms of the additional computing power required, and (as the weights are determined independently for each model grid point and time step) data gaps and/or varying locations of the measurements can easily be taken into account. In the next section we describe the model into which this nudging scheme was implemented and the experiments that have been performed.

### 3 Model and experiments

#### 3.1 Model and model set-up

The simple nudging scheme described in section 2 was implemented into the regional ocean model TRIMGEO (Tidal Residual and Intertidal Mudflat Model with geographical coordinates) set-up for the North Sea. The model operates on an Arakawa C-grid [Mesinger and Arakawa, 1976] and is based on the primitive equations. More information about the model can be found in Casulli and Cattani [1994] and Casulli and Stelling [1998]. Generally, the model equations are solved on a three-dimensional grid. However, as model experiments for the North Sea show only minor differences between two and three-dimensional simulations when sea level variations are analyzed [Kauker and Langenberg, 2000] and as we restrict ourselves to the assimilation of tide gauge data, a two-dimensional depth-averaged version of TRIMGEO was used in our experiments.

The model was integrated at a spatial resolution of  $\frac{1}{6} \times \frac{1}{10}$  degree in zonal and meridional direction respectively. The model domain extends from  $4.25^\circ$  West to  $13.42^\circ$  East, and from  $48.55^\circ$  to  $59.75^\circ$  North. A time step of 10 minutes was adopted. The bathymetry (Fig. 1) was provided by the German Federal Maritime and Hydrographic Agency (BSH) and is identical with the one used in their operational storm surge forecast system. The model was run with open boundaries at  $59.75^\circ$  N and in the English Channel, while in the eastern part of the model domain, closed boundary conditions were adopted. At the open boundaries sea level was prescribed from the amplitudes and phases of 17 major tidal constituents. Fresh water inflow from the Baltic Sea was parameterized as  $0.01498 \text{ m}^3\text{s}^{-1}$  [OSPAR Commission] and the input of the 33 largest rivers was taken into account using climatological values obtained from the operational forecast system at the BSH (Esselborn, pers. comm. 2003).

#### 3.2 Experiments, data and validation strategy

A total number of 10 experiments was performed. The first experiment, hereafter referred to as CTL, represents a control simulation in which the model was integrated without data assimilation. In all other experiments data assimilation by nudging sea level anomalies from different tide gauges as described in section 2 was performed.

Three experiments were performed to investigate the effects of different tide gauge locations on the modeled sea level variations. As tides and surges in the North Sea propagate in an anti-clockwise direction [Pugh, 1987] the geographical positions of the assimilated tide gauges are expected to have strong influences on the model results. Three different tide gauges along the English coast have been selected to test for these effects: Aberdeen, Whitby and Cromer. The experiments are referred to as *Aberdeen only* (ABE), *Whitby only* (WHI),

and *Cromer only* (CRO). The positions of these tide gauges can be inferred from Figure 1). In these three experiments the nudging coefficient  $\alpha$  (Equation 2) was set to unity and a characteristic length scale (Equation 2) of 60 km was adopted for ABE and CRO while 30 km have been chosen for WHI.

In a second set of 6 experiments data from 17 tide gauges along the British coast were assimilated. These experiments have been performed to test different parameter combinations of the characteristic length scale and the nudging coefficient and to investigate to what extent additional improvement in the representation of sea level variations can be obtained in comparison to the experiments in which only data from single tide gauges have been assimilated. In these experiments the nudging coefficient  $\alpha$  was varied between 0.5 and 1.0 and different length scales of 60 km and 30 km have been applied. A list of all parameter combinations and acronyms used for the experiments is given in Table 1.

While the characteristic length scale  $L$  already provides the radius around each tide gauge within which observations from this station will have a significant *direct* effect on the model values an additional constraint was applied: Irrespective of the actual value of  $L$  no nudging was performed for model grid points more than 100 km away from the tide gauge position. In particular in regions that are characterized by complicated tidal regimes, such as for instance tidal inlets or near the interception of different amphidromic regimes, this prevents these model grid points from being influenced by observations with potentially different tidal characteristics. An equally plausible option would have been to adopt the nudging coefficient  $\alpha$  and the characteristic length scale  $L$  separately for each station and model grid point.

In all 10 experiments the model was driven by identical sea level pressure (SLP) and near-surface wind fields obtained from a regional multi-decadal atmospheric reconstruction [Feser *et al.*, 2001] driven by the National Centers for Environmental Prediction (NCEP) re-analysis [Kalnay *et al.*, 1996]. In this regional atmospheric reconstruction special emphasis was given to the quality of near-surface marine wind fields [Weisse *et al.*, 2003] and Weisse and Feser [2003] have shown that the modeled wind fields compare well with in-situ measurements. Because the spatial resolution of the atmospheric data is about  $50\text{ km} \times 50\text{ km}$  they have been interpolated bilinearly to our ocean model resolution for this study.

In all experiments the model was integrated for the 23 month period from January 2000 to November 2001 and full model output was stored every 30 minutes. Data from British tide gauges that have been used for assimilation have been available every 15 minutes. For the experiments they were linearly interpolated to the model time steps. A set of independent tide gauges was used for the assessment of the improvements achieved from the assimilation experiments. The set comprises three Norwegian and five German stations. Data from the Norwegian stations were available every 10 minutes while the German stations have different sampling intervals, ranging from one minute to one hour. The positions of all tide gauges can be inferred from Figure 1. In the following, all comparisons between model and tide gauge values are made for anomalies with respect to mean sea level.

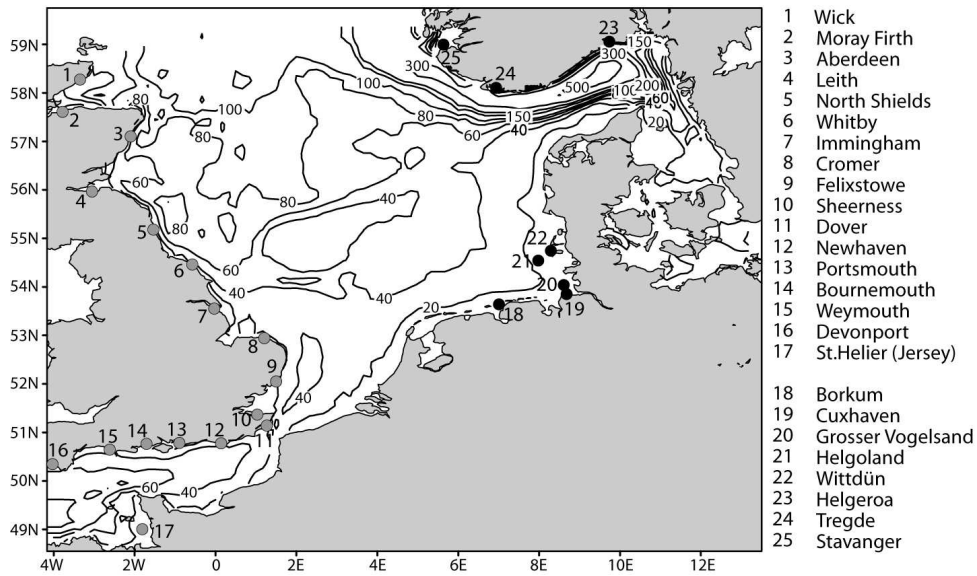
Experiment	$L$	$\alpha$
ABE	60 km	1.0
WHI	30 km	1.0
CRO	60 km	1.0
N6U	60 km	1.0
N69	60 km	0.9
N65	60 km	0.5
N3U	30 km	1.0
N39	30 km	0.9
N35	30 km	0.5

**Table 1:** The different parameters in the assimilated experiments.

## 4 Results

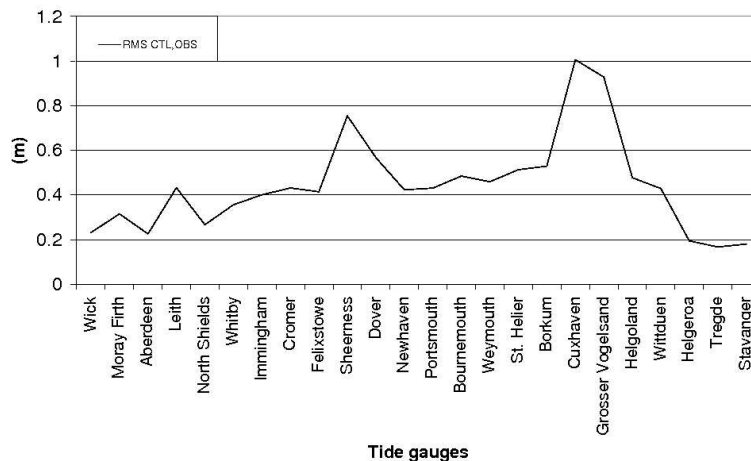
### 4.1 Validation of the Control Simulation

We first investigate the extent to which the control simulation is capable of reproducing observed sea level fluctuations. Figure 2 shows the root-mean-square error (RMS) (e.g., von Storch and Zwiers 1999) between modeled and observed sea level anomalies for the CTL experiment. For the 17 British tide gauges, used later for assimilation in the various experiments, the RMS ranges between about 0.2 and 0.6 m, with increasing values



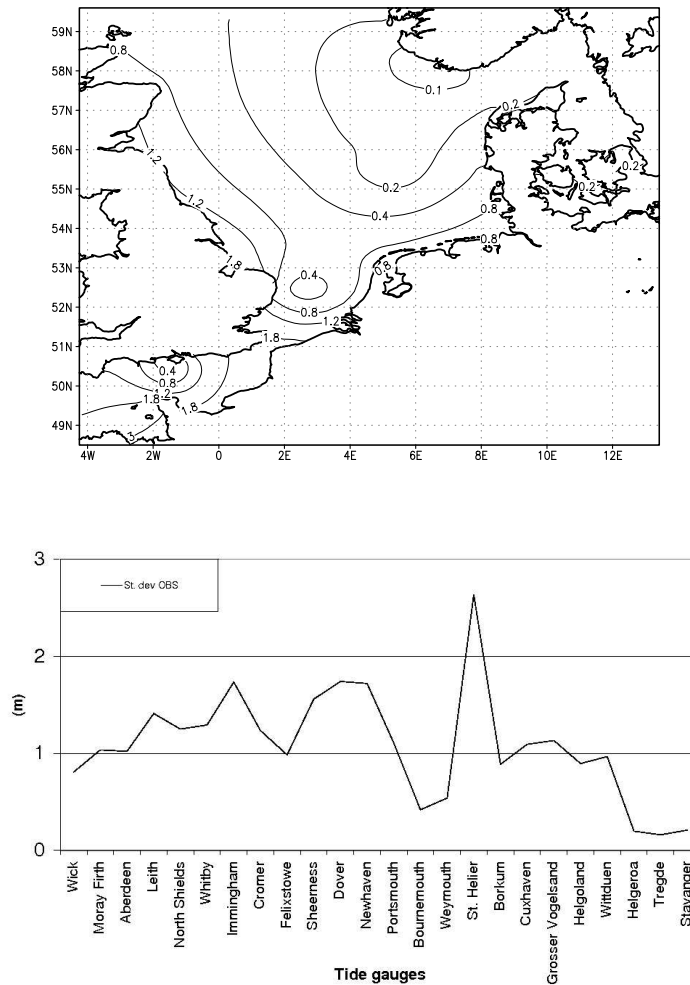
**Figure 1:** Bathymetry and location of the tide gauges used for assimilation (nr. 1-17 in grey) and validation (nr. 18-25 in black). Contour lines are drawn for 20, 40, 60, 80, 100, 150, 300 and 500 meters depth.

from North to South. An exception is provided by Sheerness for which a RMS of nearly 80 cm was found which may be a result of the relatively coarse spatial resolution in our simulations. Apart from Sheerness, largest RMSs were found for two German tide gauges, namely Cuxhaven and Grosser Vogelsand, both located in the German Bight.



**Figure 2:** Root-mean-square-error (RMS) between observed and modeled sea level heights in the control simulation for the used tide gauges. The analysis was made with available hourly data for the period 01 January 2000 until 30 November 2001

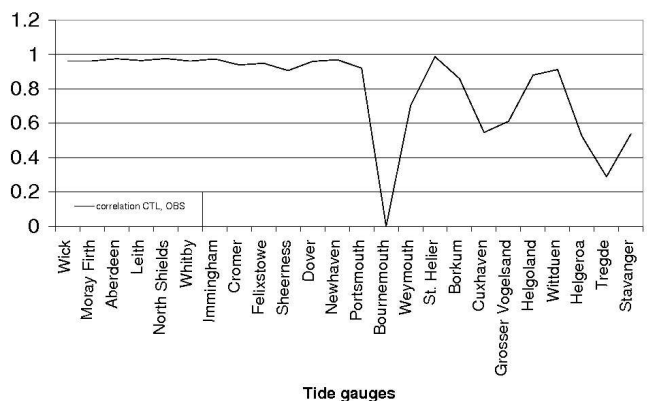
Generally, sea level variance in the CTL experiment is largest in the British, Dutch and German coastal zones, with largest values obtained for parts of the English Channel (Figure 3 upper panel). Smallest values were found at about  $52.5^{\circ}$  N,  $2.5^{\circ}$  E, within parts of the English Channel and off the Norwegian coast. A comparison with observed sea level variances estimated from tide gauge data shows that the variance is reasonably reproduced for some, but underestimated for most of the tide gauges (Figure 3 lower panel). When areas with small sea level variance are interpreted as locations of amphidromic points, Figure 3 shows that the large scale structure of the sea level variance is reasonably reproduced in the CTL experiment [cf. e.g., *Pugh* [1987]]. In combination with Figure 2 it can be further inferred that the RMSs have a tendency to increase with increasing sea level variance, that is, errors are larger for tide gauges with larger tidal and storm surge elevations.



**Figure 3:** Upper panel: Variance of sea level height in  $m^2$  obtained for the control experiment. The analysis was made with data every 30 minutes from the period 01 January 2000 until 31 December 2000. Contour lines are drawn for 0.1, 0.2, 0.4, 0.8, 1.2, 1.8 and 3.0  $m$ . Lower panel: Standard deviation of observed sea level height for the used tide gauges. The analysis was made with available hourly data for the period 01 January 2000 until 30 November 2001.

To investigate the extent to which the observed *phase*, that is, the timing of the maxima and minima, of

the tide-surge is reproduced in the CTL experiment, the correlation between observed and modeled sea level anomalies was computed (Figure 4). For the British tide gauges generally a rather good timing of the tide-surge signal can be inferred. Exceptions are provided by some tide gauges located in the English Channel where the model fails to reproduce phases adequately. The correlation systematically decreases for the German and the Norwegian tide gauges being lowest for the latter ones.



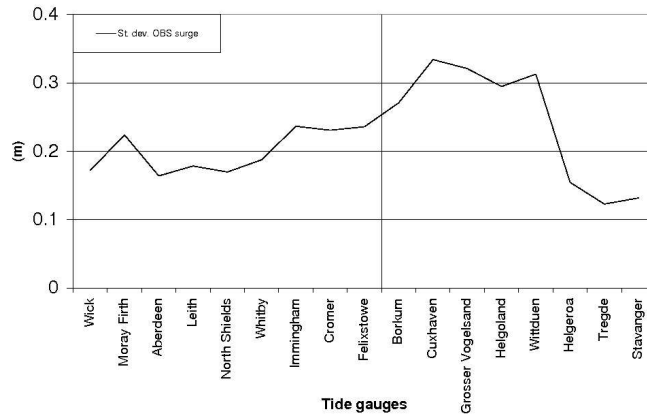
**Figure 4:** Correlation between observed and modeled sea level heights in the control experiment for the used tide gauges.

An important aspect of multi-decadal simulations is the extent to which they reproduce the observed natural variability. For storm surges the observed variability is shown in Figure 5 in the form of the standard deviation. It can be inferred that the storm surge variability is generally rather low along the British coast (in the order of about 0.2-0.25 m). It increases towards the German coast where it reaches maximum values of almost 0.35 m near Cuxhaven and then again decreases towards the Norwegian coast where it is again below about 20 cm. For the control run Figure 6 shows the ratio of the modeled and the observed storm surge variance. Generally it can be inferred that away from the open boundaries the model shows some skill in reproducing the observed storm surge variability. Near the Southern British and along the German coast about 80% of the observed variability are reproduced. Towards the open boundaries the ability of the model to reasonably simulate the storm surge variance decreases. Near Wick and Stavanger only about 50% of the observed variance are reproduced

## 4.2 Analysis of the Data Assimilation Experiments

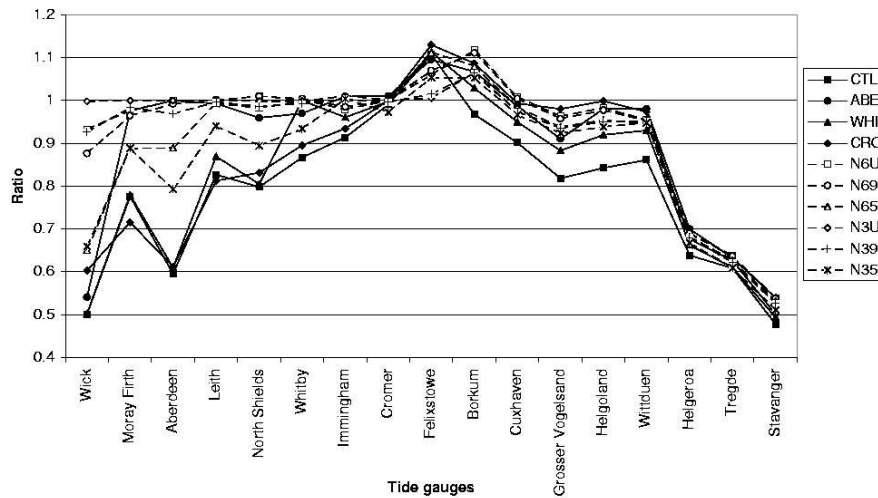
So far we have investigated the extent to which the CTL simulation is capable of reproducing observed the sea level variations. In the following we elaborate on the improvements that may be achieved by the application of our simple nudging scheme.

Fig 6 shows the ratio of the modeled and the observed surge variability for the different data assimilation experiments. Compared to the CTL experiment, all nudging experiments show a considerable improvement in the representation of the storm surge variability. The three experiments ABE, WHI, and CRO provide a clear indication on how the assimilated information propagates through the model domain. Taking into account that the tide and surge signals mainly propagate in an counter-clockwise direction through the North Sea (e.g., *Høyer and Andersen 2003, Pugh 1987*), in all three experiments almost no improvement is found upstream of the respective station ABE, WHI or CRO. In Figure 6, upstream locations are found on the left hand side of ABE, WHI and CRO, respectively. Downstream of ABE, WHI, or CRO (stations on the right hand side of



**Figure 5:** Standard deviation of the calculated surge for observed sea level heights for North Sea tide gauges.

ABE, WHI, CRO in Figure 6) more or less strong improvements were obtained. These are most visible for the Southern UK and the German coast where they are in the order of 10-20% while they are much smaller for the Norwegian stations.

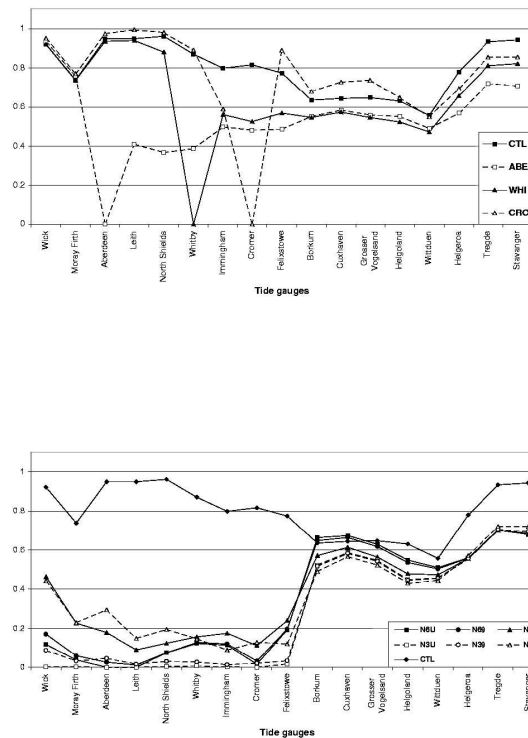


**Figure 6:** Ratio of standard deviations of the surge in the different experiments and the observed surge standard deviation.

A similar result is obtained when the RMS between modeled and observed storm surges are analyzed (Figure 7). The latter does provide not only an indication of the ability of the model to adequately represent



the storm surge statistics but also of the capability to reasonably simulate individual events. For the three experiments ABE, WHI and CRO Figure 7 shows that also for the representation of individual events most of the improvement was obtained downstream of the respective tide gauge. Along the German coast results from the ABE and WHI experiment are comparable while the CRO simulation resulted in a somewhat larger RMS.



**Figure 7:** RMS between calculated surge from the experiments and from the observations normalized with standard deviation of the observed surge (Figure 5) for North Sea tide gauges. Top: The CTL experiment and the assimilated experiments, with one tide gauge assimilated. Bottom: The fully nudged experiments.

Figure 6 shows the extent to which additional improvement in the representation of the storm surge variability and the instantaneous sea level variations can be achieved when data from more than one station are used for the assimilation. It can be inferred that apart for the very near surrounding of the station the improvement is marginal. This is particularly true for the German and Norwegian stations that have not been used for data assimilation in any of the experiments. A similar conclusion also holds for the instantaneous storm surge variations (Figure 7).

The simple nudging scheme applied in our experiments contains two tunable constants for which only ad-hoc assumptions are available. In order to test the sensitivity of our findings to different combinations of these parameters additional experiments have been performed (Table 1). Figure 6 again shows the standard deviation of modeled and observed storm surges for the different experiments. It can be inferred that while there are major differences near the British tide gauges that have been used for data assimilation, the sensitivity of the results near the German and Norwegian validation stations is small. When instantaneous differences between observed

and modeled storm surges are compared the situation is slightly different (Figure 7). Here, the experiments with a characteristic length scale of 30 km generally do show better agreement with observations than those with a length scale of 60 km. The exact value of the nudging coefficient has negligible influence on the results.

## 5 Summary and discussion

A simple and cost efficient nudging scheme suitable for multi-decadal ocean model integrations was implemented into a North Sea version of the regional ocean model TRIMGEO and has been tested for a 23 month period from January 2000 to November 2001. Compared to a control simulation that did not utilize any form of data assimilation the simulation of near-coastal sea level elevations and storm surge variations improved considerably when the nudging scheme was applied.

It was found that the model provides a reasonable representation of the storm surge variation in the inner domain away from the open boundaries. Close to the open boundaries storm surge variability is systematically underestimated by up to 50%. When observational data were assimilated into the model this situation improved considerably, especially near the north-western part of the open boundary where the data have been assimilated. Near the eastern part close to the Norwegian stations the situation remained almost unchanged while in the inner domain some improvement was found also for the German tide gauges. This result is probably caused by a combination of boundary effects and external processes not accounted for in the present set-up of the model. Boundary effects may comprise artificially limited fetches near the open boundary and may be particularly important in the vicinity of the boundary. Unaccounted external processes involve for instance so-called external surges. External surges refer to storm surges that are generated in the North Atlantic and subsequently propagate into the North Sea. Here they provide an essential contribution to the overall storm surge variability, and in particular to extreme events (e.g., *Koopmann* 1962). In the present set-up of our ocean model, contributions from external surges and other processes originating from outside the model area are not taken into account and natural variability and extreme events may therefore be underestimated. The latter may be particularly relevant for the Southern North Sea coast located in the inner model domain.

When observational data were assimilated into the model the statistics of the storm surges improved considerably. An equally plausible alternative would comprise an enlargement of the model domain such that boundary effects become less important in the North Sea and that external processes are more reasonably captured. An example of this approach can be found for instance in (e.g., *Flather et al.* 1998) where a coarse grid model run was set-up for the North Atlantic that finally provides the boundary conditions for a high-resolution North Sea simulation. While this set-up is optimal for operational purposes it may reach its limits for multi-decadal simulations, especially when particularly high-resolutions are required near the coast. In this case data assimilation provides an option to reduce boundary effects and to take those processes into account that are unresolved due to the smaller model domain.

For our analyses the available tide gauge data were divided into an assimilation and a validation data set. The assimilation data set comprises data from the 17 British tide gauges while the validation set consists of the German and Norwegian stations. This separation was motivated mainly by the prevailing counter-clockwise large-scale circulation and the tidal regime of the North Sea (e.g., *Høyer and Andersen* 2003) and was performed such that upstream/downstream tide gauges have been used for assimilation/validation respectively.

It was found that simulation of storm surge statistics improved considerably for the validation stations when data from one or more British tide gauges have been assimilated into the model. The improvement is most obvious for the German tide gauges and negligible for the Norwegian ones. Most improvement was obtained already when only data from one British tide gauge have been assimilated, and additional tide gauges in the assimilation process had only minor effects. This finding may have two important consequences for operational storm surge modeling: First, when data from an as upstream as possible tide gauge are assimilated, the largest

improvement for most of the coastal areas can be expected. In addition, the lead time for warnings would be largest. Second, in case data from a particular station are sometimes not available in real-time, this station can be replaced by another one without having major consequences on the quality of the expected results.

Presently a large variety of more or less sophisticated data assimilation techniques does exist. In ocean modeling so far all efforts have focused on the simulation of relatively short periods up to a couple of years. Because of the extensive computer resources required by the more advanced assimilation schemes, to our knowledge no multi-decadal simulation utilizing any form of data assimilation has been performed so far. The nudging scheme proposed in this paper represents a relatively simple and cost-efficient option to do so. While it may not compete with more advanced techniques for short integration periods, it represents a choice for long-term simulations as the additional computing resources required are marginal.

While a number of options exists regarding the variables and the sources of data used for assimilation in short-term integrations, additional constraints apply for multi-decadal hindcasts. In particular the data used should be available on multi-decadal time scales, should have sufficient accuracy and sufficient homogeneity on multi-decadal time scales, and should be available at high spatial and temporal resolution. In this paper we therefore limited ourselves to the assimilation of coastal tide gauges that represent one of the best options to meet those requirements.

Summarizing, we propose that the simple and cost-efficient nudging scheme presented may represent an adequate tool to assimilate tide gauge data that are sufficiently homogeneous on a multi-decadal time scale into long-term regional ocean model simulations.

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