Ocean Modelling 118 (2017) 59–72

Contents lists available at ScienceDirect

Ocean Modelling

journal homepage: www.elsevier.com/locate/ocemod

Sea level modelling in the Baltic and the North Sea: The respective role of different parts of the forcing

Magnus Hieronymus*, Jenny Hieronymus, Lars Arneborg

SMHI, Folkborgsvägen 18, Norrköping 60176, Sweden

ARTICLE INFO

Article history:
Received 16 March 2017
Revised 7 August 2017
Accepted 14 August 2017
Available online 15 August 2017

MSC:
00-01
99-00

Keywords:
Baltic Sea
Sea level
North Sea
Wind stress
Storm surges
Tides
Pressure

ABSTRACT

The effects of winds, tides, sea level pressure and storm surges on sea levels are quantified in a regional model for the North Sea and The Baltic Sea. The sea level variability in the two different basins have different primary drivers. The variability in the North Sea is mostly tidal, while most of the variability in the Baltic Sea is wind driven. A factorization technique is used to separate the effects of the different forcings, as well as the effects of interactions between different forcings. The interactions are found to have a positive feedback on the sea level variability in the Baltic Sea, and to be mostly damping in the North Sea. How sea level signals are transmitted through the domain is also studied using transfer function, and the transmission between the basins is found to be strongly damped for high frequency variability. Lastly, the effects of the different forcings on the sea level distributions in the model are also quantified, and large differences are found between the two basins.

1. Introduction

Sea level modelling and prognostics is becoming an increasingly important part of the work load of weather services world-wide. High resolution modelling is key for accurate sea level prognostics, and regional models are therefore the primary work horses utilised in this undertaking. The existence of open boundaries in the computational domain is an added complexity in regional modelling as compared to global modelling, and the influence of the boundary conditions on the sea level prognostics depends in a complex manner on many factors such as for example: the distance from the boundary, basin geometry and wind patterns. Even the mathematical formulations of open boundary conditions is a science in itself (Oliger and Sundstrom, 1978; Marchesiello et al., 2001). In this paper we will study different aspects of sea level modelling using a simplified version of the regional ocean model NEMO-Nordic (Hordoir et al., 2013; 2015). NEMO-Nordic is an adaptation of NEMO (Madec and The NEMO Team, 2016) that covers the North Sea and the Baltic Sea. The model is currently used both operationally and by the research department at the Swedish meteorological and hydrological institute (SMHI). The two ocean basins, the Baltic and the North Sea, are quite different. The Baltic Sea is a semi-enclosed brackish basin that has very small tidal amplitudes and is rather well protected from Atlantic storm surges, while the North Sea is directly connected to the Atlantic, has strong tides and is strongly affected by Atlantic storm surges. The sea level variability in the two different basins thus have different primary drivers.

Sea level research in the two basins have largely focused either on the impacts of climate change on sea levels (see e.g. Meier et al. 2004; Woth et al. 2006; Hünicke 2010) or on understanding and quantifying sea level variability on different time scales (see e.g. Samuelsson and Stigebrandt 1996; Andersson 2002; Dangendorf et al. 2013). Furthermore, most sea level research has primarily focused on mean sea levels, although there has been an increasing interest in extreme sea levels in recent years, see for example Gräwe and Burchard (2012) or Dangendorf et al. (2016). The focus of this article is somewhat different from these traditional lines of inquiry. The aim of our analysis is to separate the effects of the different parts of the forcing on sea level variability. To this end we use a factorisation technique described in Stein and Alpert (1993). The factorisation analysis shows how the individual parts of the forcing contribute to the sea level variability, as well as the contributions from interactions between different parts of the forcing. Apart from some earlier work on tide-surge interactions in the North Sea (see e.g. Horsburgh and Wilson, 2007) the effects of

* Corresponding author.
E-mail address: hieronymus.magnus@gmail.com (M. Hieronymus).

http://dx.doi.org/10.1016/j.ocemod.2017.08.007
1463-5003/

interactions between different parts of the forcing is largely unexplored in the two basins. In fact, as far as the authors are aware this is the first attempt to fully quantify the sensitivity of sea level variability to its forcing in any ocean basin.

A last focal point is on the transfer of information from the North Sea into the Baltic Sea. It is well known that the Danish Straits that separates the two basins acts as a filter for high frequency variability (Samuelsson and Stigebrandt, 1996; Carlsson, 1998), and that they are efficiently filtering the tides leaving the Baltic Sea nearly tide free. We will investigate in detail how the signal of wind driven Atlantic storm surges travel through the North Sea and into the Baltic Sea.

The remainder of the manuscript is structured as follows: Section 2 contains a model and methods section that presents the model, the runs and gives a more detailed description of the factor separation technique. Section 3 is a results section discussing model performance, the roles of the different parts of the forcing, the signal propagation from the North Sea into the Baltic Sea and how the distributions of sea levels are affected by the different forcings. Section 4 contains the conclusions.

2. Model and methods

2.1. Model description

The ocean model used in this paper is a simplified version of the NEMO-Nordic model (Hordoir et al., 2013; 2015). The model has an open boundary in the south west in the English channel and one in the north between Northern Scotland and Southern Norway. Our model runs at a resolution of two nautical miles, and has two vertical terrain following levels[1] (Song and Haidvogel, 1994). We use a constant density ($\rho = 1030\,\mathrm{kg\,m^{-3}}$) everywhere, which eliminates the need for the tracer transport schemes, as well as the need to calculate surface heat fluxes. Evaporation is modelled simply as being precipitation multiplied by 0.8, which is an average value for the Baltic Sea (Rutgersson et al., 2002). The vast majority of the freshwater input into the Baltic comes from rivers so this unusual treatment of evaporation has no significant effect on the results. Horizontal momentum diffusion is aligned along the layers and uses a fixed turbulent viscosity of $10\,\mathrm{m^2\,s^{-1}}$. The vertical viscosity is also fixed and has a value of $1\,\mathrm{m^2\,s^{-1}}$. Bottom friction is quadratic and uses the loglayer approximation (Madec and The NEMO Team, 2016). The drag coefficient at the ocean-atmosphere interface is parametrized as a linear function of the wind speed, given as

$$C_d = 10^{-3}(0.78 + 0.1|\mathbf{u_{10}} - \mathbf{u_s}|) \quad (1)$$

where $\mathbf{u_{10}} = (u_{10}, v_{10})$ is the air velocity at 10 m, and $\mathbf{u_s} = (u_s, v_s)$ is the water surface velocity.

The model is forced with dynamically downscaled ERA40 forcing (Uppala et al., 2005. The downscaling is done using the atmospheric model RCA4 (Samuelsson et al., 2011; Berg et al., 2013) to a spatial resolution of 11 km and a temporal resolution of 1 h. River run-off data comes from the HYPE model (Donnelly et al., 2016). The open boundary forcing consists of nine tidal components and wind-driven sea level variations from a simple coarse resolution barotropic storm surge model covering a large area of the North East Atlantic. Instantaneous sea level fields from the model are stored every hour.

[1] The reason why we use two levels instead of one is that the NEMO code won't run with just one level.

2.2. Experiments

The forcing of a regional ocean model can be separated into a surface and a boundary part, where the boundary part is given by the open boundary conditions (storm surges and tides) and the surface part is given by the upper boundary conditions (winds and sea level pressure). The freshwater budget (evaporation, precipitation and run-off) is also a part of the surface forcing.

Our main set of experiments is designed to separate the effects of the boundary and surface components of the forcing. Four different sets of boundary forcing are considered: none, tides, storm surges (i.e. barotropic currents and SSH from a simple storm surge model for the North Atlantic) and tides + storm surges. Unfortunately, one cannot have nothing as a boundary condition, so none means that there are no tidal harmonics and that both the currents and the SSH (sea surface height) from the external storm surge model are set to zero. The tides case has tidal harmonics, but no external storm surge model. The storm surges case has the external storm surge model, but no tidal harmonics applied. Each of these four sets of boundary forcing is then run with four different sets of surface forcing: none, only sea level pressure, only wind stress and sea level pressure + wind stress. In total this gives us 16 different runs, all of which are run for the years 1996–2005 and a snapshot of the SSH is saved every hour. All runs are initiated with initial conditions from a run that has been run from 1961 with the full forcing set. For all comparison where we do not use the full forcing set we therefore use the years 1997–2005, unless otherwise is stated. This is to ensure that sea level variability seen in the different runs is only due to the prescribed forcing. A few additional runs where boundary forcing from different years are used together with surface forcing from a fixed year are performed and used in Section 3.3, and the details of those runs are given there.

2.3. The Stein and Alpert (1993) factorisation

The factorisation method of Stein and Alpert (1993) is used to compute how each factor (in our case the factors are winds, sea level pressure, tides and surges) as well as interaction between the factors contribute to sea level. The method can be applied to any variable of interest and we shall focus on the same properties that are visualized in the Taylor diagrams that are used extensively in this paper with one exception. The Taylor diagrams show the standard deviation, while we will factorize the variance. The reason for this is that for sets of random uncorrelated variables; the variance of their sum is equal to the sum of their variances, and this property is helpful when interpreting the interaction terms. The overarching idea behind the factor separation technique is that a given variable from a simulation can be written as a sum of contributions from different factors and interaction between those factors. We have chosen to use the different parts of the forcing as factors, but this is a subjective choice. The exact same methodology applies if one chooses factors such as for example bottom topography and vertical mixing. The only requirement on the factors is that one should be able to turn them on and off in the different simulations. If only one factor is considered, say winds, the system is very simple. To calculate the effect of winds on for example sea level variance one needs two simulations, one where winds are included in the forcing and one where it is not. The contribution of winds to sea level variance is then simply given by the sea level variance in the run with winds minus that in the run without. The general idea is the same when more factors are introduced, but the system gets more complex because of interactions between the different factors. A compact expression for the different factors is