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An uncoupled dynamical downscaling for the North Sea: Method and evaluation

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ABSTRACT

A reliable regional modeling system for uncoupled dynamical downscaling simulations of potential global climate change scenarios in the North Sea is presented. The HAMSOM regional shelf ocean model is forced with results from the MPIOM global ocean model at the open lateral boundaries of the model domain, and with results from the REMO regional atmosphere model at the air-sea interface. The evaluation of the model chain is based on the North Sea regionalization for the period 1951–2000 of the global historic control run 20C3M for the IPCC SRES scenario runs under the CMIP3 model generation. To reproduce reasonable long-term statistics of hydrodynamic conditions in the North Sea, a bias correction method relative to ERA40 reanalysis data and WOA-2001 climatology is applied to the forcing variables. Comparisons of the HAMSOM model results with observational water temperature and salinity climatologies are presented as well as with previously published research of volume transports, residence and flushing times, NAO correlations, surface heat and fresh water fluxes, and thermocline parameters. In general, the model results agree reasonably with the given references, thereby qualifying the presented concept as an appropriate tool for dynamical downscaling of global scenario runs for the North Sea.

1. Introduction

For the North Sea in particular, there is a long history of ocean modeling, ranging in complexity from barotropic tidal and storm surge models to three-dimensional baroclinic models with ecosystem components. Reviews of hydrodynamic modeling in the North Sea have been given by e.g. Jones (2002), Lenhart and Pohlmann (2004) and Delhez et al. (2004). Regional circulation models (RCMs) have thereby proven to be useful tools for studying regional dynamics in the ocean and atmosphere, such as ocean currents (e.g. Pohlmann, 2006; Ådlandsvik and Bentsen, 2007; Melsom et al., 2009) or energy and fresh water cycles (e.g. Jacob, 2001; Schrum et al., 2003, 2005) as well as for the prediction of climate changes on a regional scale (e.g. Schrum, 2001; Déqué et al., 2005; Meier, 2006; Ådlandsvik, 2008). There is a wide consensus in the scientific community that dynamical downscaling using RCMs is the most appropriate option for regional impact studies and vulnerability analyses related to climate change (Feser et al., 2011). Adaptation measures to climate change, as opposed to mitigation policies, are an inherent local- and regional-scale issue.

In contrast to general circulation models (GCMs), the restricted model domain of an RCM allows for long-term simulation of physical processes with a high horizontal grid resolution at comparatively low computational costs. In general, a fine resolution is important for resolving small-scale features of the circulation, e.g., near-shore processes affected by bottom topography and coastline morphology or small-scale fronts and associated baroclinic eddies and frontal jets. RCMs are also expected to simulate temporal variability more reasonably, which is often a weakness of GCMs.

The objective of this paper is to present a reliable model system to be used as dynamical downscaling of potential global climate scenario runs for the North Sea. Model skills are demonstrated by application to a global ocean simulation of the historic control run 20C3M, corresponding to the IPCC (Intergovernmental Panel on Climate Change) SRES future emission scenarios (Special Report on Emissions Scenarios; Nakicenovic and Swart, 2000). In this context the CMIP3 (Coupled Model Intercomparison Project) generation of the coupled global atmosphere–ocean circulation model ECHAM5/MPIOM (European Center Hamburg Model 5th Generation/Max Planck Institute Ocean Model; Climate, 2006) is employed for the North Sea projection under the SRES A1B emission scenario (Fig. 1). The control run of ECHAM5/MPIOM as well as the subsequent A1B scenario run have already been regionalized for the greater European atmosphere by means of dynamical downscaling with the regional atmosphere circulation model REMO (Regional Model; Jacob and Podzun, 1997; Jacob et al., 2001). Thereby, results of the atmosphere model ECHAM5 have been used to prescribe the conditions at the open lateral boundaries of the regional domain,

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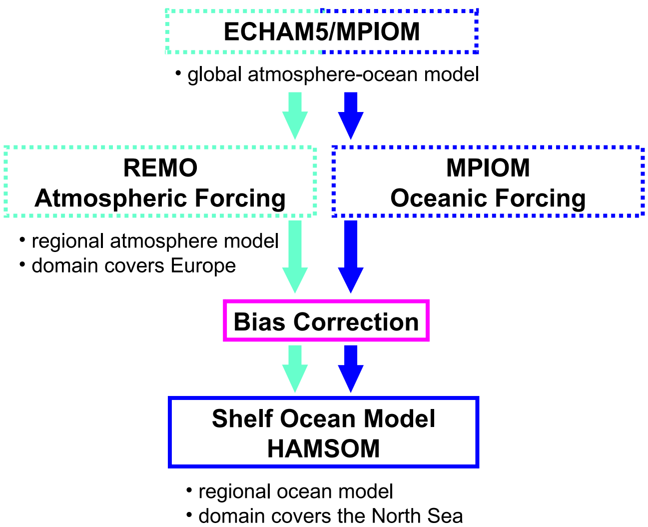

Fig. 1. Schematic model setup of the uncoupled dynamical downscaling for the North Sea.

whereas the results of the ocean model MPIOM (Marsland et al., 2003; Roeckner et al., 2006; Jungclaus et al., 2006a) have been used to prescribe sea surface conditions. Atmosphere-land interactions are fully implemented in REMO and therefore are not required to be prescribed. These model simulations have been carried out by the community of the Max Planck Institute for Meteorology (Hamburg, Germany). In the present study, the results of REMO and MPIOM are used analogously to drive the shelf ocean model HAMSOM (Hamburg shelf ocean model; Backhaus, 1985, 1990; Pohlmann, 1991, 1996a,c).

The involved model simulations always cover the time period 1951–2099 as being composed of the control run 1951–2000 and the A1B scenario run 2001–2099. The forcing data for the control run originate from the historic ECHAM5/MPIOM model run 20C3M for the 20th century, initialized in the year 2240 of a preindustrial spin up run, which is defined as representing the year 1860. This run was then continued until the year 2000 with observed anthropogenic greenhouse gas concentrations.

In the present study, the control run was used to evaluate and improve the boundary conditions extracted from REMO and MPIOM, as well as the HAMSOM model configuration itself, by comparing model results with observations and reanalysis data. However, in order to be consistent with the scenario simulation, the control period was also run in free mode, that is, without any data assimilation incorporated. In such a free run, the actual weather events certainly cannot be reproduced so that any modeled time series are expected to deviate from observations or reanalysis data. Nevertheless, the present climate statistics should be simulated adequately in order to assign any degree of reliability and confidence to specific future scenario runs. The evaluation procedure is thus based on the comparison of monthly climatological means derived both from the 50-year control period, regarded as statistically representative long-term model characteristics, and from observations or reanalysis data.

2. Material and methods

The restriction to a certain geographical region and the aim to simulate physical processes on climatological time scales (i.e. 30 years or more) implies that information on the large-scale state of the ocean or atmosphere outside the regional model domain needs to be provided by another source. These lateral boundary conditions can be extracted from GCM simulations or from global-scale observations and re-analysis products, where the RCM is said to be nested into the respective large-scale forcing. This technique is referred to as dynamical downscaling and, as in the present study, is usually carried out in a one-way mode, that is, without feedback to the large-scale system. Hence, the RCMs inherit any large-scale error from the parent global model via the lateral boundary conditions (Pielke and Wilby, 2012). Beyond the aforementioned advantages, the uncertainty of a given global climate projection is therefore not reduced by the method of one-way nesting. In recent years, however, two-way nesting methods have also been developed (e.g. Lorenz and Jacob, 2005), that are able to effect the large-scale circulation, at least if the dynamics of the downscaling region significantly contributes to it.

2.1. Regional shelf ocean model HAMSOM

The Hamburg shelf ocean model HAMSOM (Backhaus, 1985, 1990; Pohlmann, 1991, 1996c,a) is a three-dimensional baroclinic hydrodynamic model based on the finite difference method. The underlying primitive equations of motion are defined in z-coordinates on an Arakawa C-grid, where the hydrostatic and Boussinesq assumptions are implemented. Major stability constraints for surface gravity waves and the heat conduction equation are avoided by the implementation of implicit schemes. The employed turbulence closure scheme is related to a Mellor–Yamada level-2 type formulation (Mellor and Yamada, 1974), while a higher order scheme is incorporated for the Coriolis rotation in time. At the open lateral boundaries, a modified Sommerfeld radiation condition according to Orlanski (1976) is specified for outflow conditions. For the discretization of the North Sea domain shown in Fig. 2, a quasi-orthogonal spherical grid is used which provides a meso-scale horizontal resolution of $1.5'$ lat. $\times$ $2.5'$ lon. ($\sim$3 km). The maximum depth of 700 m is divided into 30 layers with successively increasing layer thickness from 5 to 50 m. The horizontal meso-scale resolution corresponds to the baroclinic Rossby radius of deformation in the North Sea. The model thus permits for small-scale fronts and associated baroclinic eddies and frontal jets. Since a maximum water depth of about 150 m is not exceeded in the North Sea despite the Norwegian Trench, the horizontal resolution of just 3 km still yields an aspect ratio of 1/20, justifying the application of the shallow water equations in the model. The time step size is 5 min, where the forcing variables are updated every second time step via linear interpolation.

2.2. Forcing data

2.2.1. Lateral open boundaries

The open lateral boundaries of the North Sea model domain consist of the connections to the North Atlantic and Norwegian Sea as the western and northern boundaries, the English Channel as the southern boundary and the Arkona Sea (connection to the Baltic Sea) as the eastern boundary. However, due to the geographic peculiarity of the Baltic Sea as being a semi-enclosed marginal sea itself with no other connection to the open ocean than the North Sea, in the present study the eastern boundary is represented by conditions normally applied to river input cells (see Section 2.3). At each open boundary section, the three prognostic variables water temperature, salinity and sea surface height (SSH) are prescribed as driving variables to force the HAMSOM model. They are extracted from the MPIOM results of the global coupled ECHAM5/MPIOM climate simulation provided as monthly means, while the same global climate simulation also provided the boundary data for the atmosphere regionalization with REMO (Fig. 1). Currents across open boundaries are induced in HAMSOM

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