Annex 2: Climate Model Simulations for the North Sea Region

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A2.1 Introduction

Climate models are powerful tools for investigating internal climate variability and the response of the climate system to external forcing, complementing observational studies.

Internal climate variability depicts natural variations due to chaotic processes within the climate system. On annual to multi-decadel time scales internal variability largely arises from the continuous interaction between the atmosphere and the ocean. External forcing involves factors outside the climate system and comprises natural forcing factors (e.g. solar variability, orbital variations or volcanic eruptions) and anthropogenic forcing factors (e.g. emissions of greenhouse gases to the atmosphere, anthropogenic aerosols and changes in land use). Climate variations due to internal processes and external forcing occur at different spatial scales (due to the different spatial extent of the relevant processes) and at different temporal scales (due to the different time scales of the relevant forcing factors and the different response times of the climate system components).

In order to simulate internal and externally driven variability at different temporal and spatial scales with climate models, the relevant components and processes need to be included in the model. To investigate climate system processes, a realistic representation of the coupling between atmosphere and ocean is essential. For this purpose, climate simulations are carried out using coupled Atmosphere–Ocean General Circulation Models (AOGCMs). Such models are able to represent dynamic interactions between atmosphere, ocean and land, and thus also related non-linear feedbacks in the climate system. State-of-the-art Earth System Models (ESMs), which constitute a further development of AOGCMs, also include dynamic land and ocean biosphere models and represent the carbon cycle, and in some

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cases ice sheet dynamics, aerosol processes and atmospheric chemistry.

A major application of climate models is the simulation of potential future climate changes due to human action within the climate system. Future climate change in the near term (at the scale of several decades) cannot be predicted, due to internal climate variability and unknown external forcings. However, it is possible to examine the impact of some external forcing over the longer term. For example, by using anthropogenic greenhouse gas emission scenarios to project potential future climate evolutions over the coming century and beyond. Each projection is the combined result of the forced climate change signal and a possible course of internal variability under that scenario. Any two projections with one model and for one emission scenario may thus differ with respect to the simulated course of internal variability.

To assess the climate of the North Sea region, regional data from global models are dynamically downscaled using regional climate and ocean models to resolve regional-scale processes in more detail than can be shown at the far coarser resolution of global models. Recent studies for the North Sea region have also applied coupled regional atmosphere–ocean models in order to represent mesoscale feedbacks. One subtask of the German research program KLIWAS is to focus on coupled regional model simulations for the North Sea region.

A2.2 Climate Models

Climate models are models of the climate system based on physical, chemical and biological principles. They can be classified into conceptual models (e.g. one-dimensional energy balance models), earth system models of intermediate complexity (EMICs) and comprehensive global climate models, which are three-dimensional general circulation models (GCMs). Key components of GCMs are atmosphere and ocean general circulation models (AGCMs and OGCMs), which can be dynamically coupled to form atmosphere–ocean general circulation models (AOGCMs). In state-of-the-art Earth System Models (ESMs), further components of the climate system such as ice sheets, vegetation dynamics and biogeochemical cycles may be included. An introduction to climate modelling is given by McGuffie and Henderson-Sellers (2005).

For spatial refinement of GCM simulations, statistical and dynamical downscaling methods are applied. For statistical downscaling, statistical relationships between observed local and large-scale variables are established and then applied to GCM output. According to Wilby and Wigley (1997), statistical downscaling is divided into regression methods, weather pattern-based approaches, and stochastic weather generators. Regression methods are usually applied because they are easy to implement and computationally efficient. Among other things, statistical downscaling has been applied to estimate biological impacts and changes in sea level. For the latter, projected future large-scale meteorology, typically taken from GCMs, is related to local extreme sea level using statistical relationships derived from observations or a limited number of simulations from physically-based models (for a review see Lowe and Gregory 2010). It is unclear how statistical relationships derived from observations or simulations of the past will continue to be applicable under future climate conditions. In the rest of the annex, only dynamical downscaling methods are considered.

Dynamical downscaling involves regional climate models (RCMs). Reviews about RCMs are given, for instance, by Rummukainen (2010) and Rockel (2015). RCMs are local area circulation models for a three-dimensional section of the atmosphere at high spatial resolution, forced by large-scale atmospheric conditions simulated by a GCM. Regional ocean models are circulation models for a three-dimensional section of the ocean, forced by large-scale ocean conditions simulated by a global ocean model, and meteorological forcing from atmospheric models. As in the case of global models, regional models of atmosphere and ocean can be coupled to form regional atmosphere–ocean models, and further complemented by additional components of the climate system, towards regional climate system models.

A2.2.1 Atmosphere–Ocean General Circulation Models

Fluid dynamics and thermodynamics in the atmosphere and ocean are described by fundamental physical laws as the conservation of momentum, mass and energy, and the thermodynamic equation of state. They form a system of non-linear partial differential equations for which no closed analytic solution exists. Rather, they need to be discretised using either the finite difference method or the spectral method and solved numerically. For finite differences, a grid is imposed on the atmosphere and ocean. The grid resolution strongly correlates with available computer power. Typical horizontal resolutions of AGCMs for centennial climate simulations correspond to spatial scales of between 300 and 100 km, in some cases 50 km, with 30–90 vertical levels. Horizontal resolution in OGCMs corresponds to spatial scales of between 160 and 10 km, with 40–80 vertical levels.

Processes which are not resolved at the resolution of the model grid need to be considered by describing their collective effect on the resolved spatial unit. This is done by parameterisations based on theoretical assumptions, process-based modelling or observations and derived empirical relationships. Examples for parameterised subgrid-scale processes in climate models include radiation, convection, processes within the atmospheric and oceanic planetary boundary layers and land surface processes. The fundamental physical understanding behind those parameterisations, together with the numerical methods and model resolutions applied, as well as the treatment of initial and boundary conditions, determine the capabilities of a model. In AOGCMs, the coupling between atmosphere and ocean is of crucial importance. Major difficulties with coupled models arise because the initial states of the ocean and atmosphere are not known precisely and even small inconsistencies in terms of energy, momentum and mass fluxes between atmosphere and ocean can cause a model drift to unrealistic climatic states. In early AOGCM simulations, this problem was addressed by empirical 'flux adjustments' (Manabe and Stouffer 1988). Today, most coupled models no longer need such adjustment owing to improved representation of physical processes, and to finer model resolution.

A2.2.2 Regional Climate Models

Regional climate models are models of a three-dimensional section of the atmosphere and possibly other climate system components. They are based on the same primitive equations for fluid dynamics as global climate models. They are discretised at much finer spatial atmosphere grids (corresponding to spatial scales of 50–2.5 km) for a limited geographical area. At the lateral boundaries of the model domain, meteorological conditions from either global model simulations or observational data are prescribed ('nesting'). Within the model domain, finer-scale processes such as mesoscale convective systems, orographic and land-sea contrast induced circulations are resolved. This method is also called dynamical downscaling. In terms of topography, land-sea distribution and land surface characteristics, regional climate models apply more detailed lower boundary descriptions than global climate models. Compared to global models, the treatment of lateral and lower boundary data in regional models can affect model quality.

The nested regional modelling technique essentially originated from numerical weather prediction. The use of RCMs for climate application was pioneered by Giorgi (1990). The advantages of regional atmosphere models are (1) more detailed orography and improved spatial representation of precipitation, (2) improved representation of the land-sea mask, (3) improved sea surface temperature (SST) boundary conditions if a regional coupled atmosphere–ocean model is used, (4) more accurate modelling of extremes (e.g. low pressure systems), and (5) more detailed representation of vegetation and soil characteristics over land (Rummukainen 2010; Feser et al. 2011 and references therein). Over the sea the added value of the high resolution in the regional atmosphere model is limited spatially to the coastal zone. For the North Sea, added value is found in the Southern Bight and the Skagerrak (Winterfeldt et al. 2010; Feser et al. 2011).

During the last decade, RCMs have been coupled with other climate process models, such as ocean, sea-ice and biosphere models, thus moving towards regional climate system models (RCSMs). RCSMs are able to represent dynamic interactions between the regional climate system components and thus regional-to-local climate feedbacks. RCMs are used in a wide range of applications from paleoclimate to anthropogenic climate change studies. For a comprehensive study of regional climate change in the North Sea region, coupled regional atmosphere–ocean models are appropriate tools. They provide regional to local scale climate information relevant for regional climate and climate change assessments.

A2.2.2.1 Regional Ocean Models

For a detailed and spatially resolved investigation of climate change impacts on physical and biogeochemical variables of the North Sea system a consistent dynamical downscaling approach is needed. Such an approach is usually complex and computationally expensive. It requires coupled physical-biogeochemical models of sufficiently high resolution driven with appropriate atmospheric forcing (i.e. air-sea fluxes of momentum, energy and matter including the atmospheric deposition of nitrogen and carbon), hydrological forcing (water volume, carbon and nutrient flows from the catchment area) and lateral boundary data at locations in the North Atlantic and Baltic Sea depending on the extent of the regional model domain. In addition, consistent initial conditions are needed. For reasons of computational expense, rather than simulating the full transient period from past to distant future, two or more time-slices are often used, with one covering the recent past and the others covering the mid- and/or end of the century. If time slices of present and future climates are calculated instead of the transient evolution under a changing climate, initial conditions are also needed for the future time slice. Due to the relatively short memory of initial conditions in the North Sea the proper choice of initial values for physical variables is not usually a problem. A shorter spin-up period of about 1–3 years guarantees that the state variables are in equilibrium with the model physics. For nutrient and carbon cycling, spin-up periods of 2–5 years are needed, because in the North Sea time scales of the water-sediment fluxes and the biogeochemical system are slightly longer than physical time scales.

For regional North Sea scenario simulations, initial, surface and boundary forcing data can be taken directly from

GCM simulations (e.g. Ådlandsvik 2008). However, due to the coarse resolution of GCMs these data sets suffer from considerable biases at the regional scale, which prevents the realistic modelling of regional hydrodynamic and biogeochemical processes. Either a bias correction method (see Sect. A2.3.2) or a regional atmosphere model and a hydrological model should therefore be used to force the ocean model. As both the ocean and the atmosphere need higher spatial resolution than is usually available from state-of-the-art GCM simulations, the atmospheric forcing of the regional ocean model is often downscaled as well.

A2.2.2.2 Regional Coupled Atmosphere–Ocean Models

While the coarser AOGCMs have been used for some time, a recent major achievement with respect to modelling is the building of high-resolution fully coupled atmosphere–sea-ice–ocean–land-surface models, which allow for consideration and resolution of local feedbacks (Gustafsson et al. 1998; Hagedorn et al. 2000; Rummukainen et al. 2001; Döscher et al. 2002; Schrum et al. 2003; Dieterich et al. 2013, 2014; Ho-Hagemann et al. 2013; Tian et al. 2013; Van Pham et al. 2014; Gröger et al. 2015). The first coupled atmosphere–sea-ice–ocean models were developed to improve short-range weather forecasting (e.g. Gustafsson et al. 1998) or to study processes and the impact of coupling on air-sea exchange (e.g. Hagedorn et al. 2000; Schrum et al. 2003). During the past decade, coupled modelling has become more aligned to perform studies on climate change (e.g. Rummukainen et al. 2001; Räisänen et al. 2004; Meier et al. 2011a) and the first transient centennial climate change simulations became available for the Baltic Sea region (Meier et al. 2011b, 2012a). Transient simulations for the period 1960–2100 using regional coupled atmosphere–ocean models are now available for the North Sea (initialised by the German KLIWAS project; www.kliwas.de) (Bülow et al. 2014; Dieterich et al. 2014; Su et al. 2014b) (see Sect. A2.4).

In a first attempt to model the regional coupled atmosphere–ocean system including the North Sea, Schrum et al. (2003) showed that coupling stabilised the regional model system simulation in a one-year simulation and reduced the drift compared to the uncoupled system. In a decadal simulation, Su et al. (2014b) showed that their coupled model was able to damp the drift seen in an uncoupled regional atmosphere–ocean model system, which had been due to an accumulation of heat caused by heat flux errors. Nevertheless, the impact of air-sea heat fluxes on atmospheric conditions is not the same for different periods. Kjellström et al. (2005) showed that the regional impact of surface fluxes on summer SSTs is greatest during a phase of negative NAO index, when the large-scale atmospheric flow over the North Atlantic is weaker and more northerly, than during a phase of positive NAO index, when the large-scale atmospheric flow is stronger and more westerly. Hence, the impact of the lower boundary condition on near surface atmospheric fields and atmosphere–ocean fluxes is small when horizontal advection is large, for example during years with a positive NAO index.

A2.2.2.3 Towards Regional Climate System Models

In recent years, coupled atmosphere–sea-ice–ocean models have been further elaborated by using a hierarchy of sub-models for the Earth system, combining regional climate models with sub-models for surface waves (e.g. Rutgersson et al. 2012), land vegetation (e.g. Smith et al. 2011), hydrology and land biochemistry (e.g. Arheimer et al. 2012; Meier et al. 2012b), marine biogeochemistry and lower trophic level dynamics (e.g. Allen et al. 2001; Holt et al. 2005; Pätsch and Kühn 2008; Daewel and Schrum 2013), the marine carbon cycle (e.g. Wakelin et al. 2012a, b; Artioli et al. 2013; Gröger et al. 2015, early life stages of fish (e.g. Daewel et al. 2008) and food web modelling (e.g. Niiranen et al. 2013). Hence, there is a tendency to develop Regional Climate System Models (RCSMs), which enables better investigation of the impact of climate change on the entire marine environment. Indeed, RCSMs further enable regional climate simulations which represent dynamical feedback mechanisms such as the ice-albedo feedback (Meier et al. 2011a), by including interactive coupling between the regional climate system components (i.e. atmosphere, ocean, sea ice, land vegetation, marine biogeochemistry).

A2.2.2.4 Regional Coupled Modelling of Land–Sea Processes

Many downscaling studies for the North Sea assume—because more detailed information is lacking—that runoff from the catchment area and the freshwater outflow from the Baltic Sea will not change in a future climate (e.g. Wakelin et al. 2012a). As far as is known, only in the MPIOM-REMO model is the water cycle closed (Sein et al. 2015) and no attempt has so far been made to consider terrestrial changes in nutrient loads or alkalinity at either the global scale in ESMs or for any regional ESM. Although the impact of changing runoff and river load and changing Baltic outflow properties may be restricted to the southern coastal North Sea and the Skagerrak, respectively, a more consistent approach addressing the water and nutrient budget of the North Sea should consider the entire land-sea continuum. Hence, projections of salinity and marine biogeochemical cycles in shelf seas are still uncertain (e.g. Meier et al. 2006; Wakelin et al. 2012a; Artioli et al. 2013). Recently, a new hydrological model, the HYPE model (HYdrological Predictions for the Environment) (Lindström et al. 2010; Arheimer et al. 2012), was developed to calculate river flow and river-borne nutrient loadings from catchment areas.

The HYPE model version developed for Europe is referred to as E-HYPE. In the future, scenario simulations with E-HYPE can be used to calculate changing water and nutrient budgets more consistently. However, a current limitation is that the carbon cycle and carbon loads are not considered in the present version of E-HYPE. Despite these recent efforts, the uncertainties in runoff in scenario simulations for the end of the 21st century are considerable due to biases in precipitation from the regional atmosphere models (Donnelly et al. 2014). Future projections of nutrient loads are perhaps even more uncertain than projections of future river flows, due to unknown future land use and socioeconomic scenarios (Arheimer et al. 2012).

A2.3 Climate Projections

A2.3.1 Methodology

Climate models are applied to project potential future climate evolutions at multi-decadal to centennial time scales. The temporal evolution of future climate will depend on external natural and anthropogenic forcing and on internal climate variability. The following sections explain the methodology of climate model projections, and how external forcings and internal climate variability are considered.

A2.3.1.1 External Forcing

Humans affect climate through emission of substances to the atmosphere and by altering characteristics of the land surface. Future socioeconomic development cannot be foreseen, but it is possible to assume plausible future pathways and derive related emission and land-use scenarios. Potential human pathways are described within global socioeconomic scenarios which assume certain development of demography, policies, technology and economic growth. For each scenario, the related emissions of greenhouse gases and aerosols are quantified, from which the concentrations of the respective substances in the atmosphere are derived. The procedure of defining emission scenarios is described in the Special Report on Emission Scenarios (Nakicenovic and Swart 2000). The latest generation of climate projections for the 21st century build on the more recent Representative Concentration Pathways (RCPs), which are derived from a different scenario process (Moss et al. 2010). RCPs are defined by different levels of radiative forcing at the end of the 21st century. Further information on emission scenarios and RCPs is provided in Annex 4.

The concentrations, in some cases the emissions, are prescribed to climate models, which then simulate the response of the climate system to the forcing. For historical climate simulations, observed concentrations of atmospheric substances are prescribed to the models. The results of climate projections are related to the results of the historical climate simulation in order to derive simulated climate change signals. By prescribing different forcings according to different pathways, a range of potential future climate evolutions can be projected.

Future natural external forcings such as volcanic eruptions and solar variability are not predictable. In the real future of earth, changes in natural factors may occur which could substantially affect future earth climate. This will always be an unknown in climate projections. In most climate projections for the future, natural external forcings are kept constant. For historical climate simulations they are prescribed to the models from available observations. The projected human impact on climate for the 21st century, however, seems significantly larger than the amount of natural external forcing on climate than has occurred over a multi-century and longer historical perspective.

A2.3.1.2 Internal Climate Variability

Assuming one external forcing, a range of climate evolutions are still possible due to the impact of internal climate dynamics. In addition, with external factors changing over time, the internal climate variability itself can also change over time. Internal variability arises from natural processes within the climate system and can lead to stochastic variations in climate parameters at time scales from seconds to centuries. Processes within the atmosphere occur on relatively short time scales, whereas processes within the ocean or ice sheets occur on longer time scales. Interactions and feedbacks between components of the climate system (i.e. atmosphere, biosphere, lithosphere, pedosphere, hydrosphere and cryosphere) lead to natural internal climate variations that are also relevant at the multi-decadal time scales of climate projections. Climate models are able to simulate internal climate variability, but its temporal evolution strongly depends on the initialisation of each model component. To consider different temporal evolutions of natural climate variability, a set of simulations can be performed with the same external forcing but with different initialisation states. The results of such an initial-condition ensemble for a certain time period lie within a range of equally probable climate evolutions.

A2.3.1.3 Regional Climate Change Projections

Global simulations of the historical climate and global projections of the future climate can be dynamically downscaled with RCMs, in order to relate the overall climate change to regional and local consequences in more detail. While RCMs can inherit errors from the GCMs and may also add further uncertainties due to different parameterisations, structures and configurations, they do add value to the modelling results owing to the better representation of local-scale features and processes. Thus, local-to-regional scale climate change patterns simulated by an RCM can decisively differ from the simulation results of a global model.

Models are always simplified images of the earth's climate system. They provide more or less accurate approximations of climate parameters compared to the real system. Many physical processes occur on spatial scales which are not resolved by climate models and thus need parameterisations. Model parameterisations are derived from empirical studies and statistical approaches. Modelling uncertainties arise from an incomplete understanding of processes within the climate system and from the inability to represent all processes and characteristics of the climate system accurately within climate models (see Annex 3). Modelling uncertainties can lead to systematic biases between simulated climate parameters and those based on observations. For some investigations bias correction methods are applied (see Sect. A2.3.2).

Different models apply different physical parameterisations and different numerical approaches. Those structural differences lead to a range of possible climate responses to external forcing, which is addressed with multi-model-ensemble simulations (see Sect. A2.3.3). In the case of regional climate projections, simulations of multi-global model ensembles are downscaled either with a single RCM or with different RCMs. Multi-model ensemble simulations based on a single scenario sample modelling uncertainties, but also different initial conditions of the climate system, as each global model is initialised at a different climate state.

A2.3.2 Bias Correction

To overcome shortcomings in the atmospheric and hydrological forcing and in the lateral boundary data towards the North Atlantic and Baltic Sea, bias correction methods are often applied (e.g. Holt et al. 2012; Wakelin et al. 2012a; Mathis 2013). An advantage of applying bias correction is that the projections become more reliable when the simulated historical climate is closer to the observed climate. The sensitivity of the regional system to projected regional changes is probably also described more realistically. However, a disadvantage is that the projected parameters are among each other no longer dynamically consistent. Furthermore, some bias correction methods assume that internal climate variability is not influenced by external forcing, which can lead to different climate change signals than when they are derived from the original model simulation.

Without loss of generality, the following discussion is restricted to the atmospheric forcing of a regional climate ocean model. Forcing can be handled by three approaches: (1) direct forcing with GCM output (e.g. Ådlandsvik 2008), (2) forcing with regional atmosphere model results driven by GCM data at lateral and surface boundaries (e.g. Holt et al. 2010), and (3) forcing with regional coupled atmosphere–ocean model results driven by GCM data at lateral boundaries (Bülow et al. 2014). In all three cases the atmospheric forcing may be biased compared to observations of historical climate due to the coarse resolution (Case 1), inconsistent SSTs (Case 2) or biases in the large-scale circulation (Cases 1, 2, 3). Furthermore, even in Cases 2 and 3, when a regional climate model is used, the resolution might not be high enough to resolve all the relevant processes with an impact on ocean climate.

Bias correction methods can be applied together with all three approaches. Two main categories of bias correction are the delta approach, and linear or nonlinear bias correction methods. In the delta approach, historical climate forcing is provided by reanalysis data. The climate change signal is derived through perturbing the historical climate forcing with the simulated change from a GCM or an RCM. Both additive and multiplicative perturbations have been used (e.g. Wakelin et al. 2012a; Holt et al. 2014, respectively). The second category methods apply the same, time-independent bias correction to both the historical and climate change forcing to improve agreement between the historical climate and contemporary observations. The correction might either be a linear correction (fractional or additive), for example to correct for a bias of the mean condition (e.g. Mathis 2013), or the correction might be a more complex nonlinear function derived for example from a statistical downscaling approach (e.g. Donnelly et al. 2014).

The overall disadvantage of all bias correction methods is that the simulated changes are affected by the bias correction and are sensitive to the chosen method (e.g. Räisänen and Räty 2013; Donnelly et al. 2014; Holt et al. 2014).

A2.3.3 Ensemble Simulations

Since 1990, the first model intercomparison projects (MIPs) opened a new era in climate modelling. They provide a standard experiment protocol and a worldwide community-based infrastructure in support of model simulations, evaluation, intercomparison, documentation and data access. There are, among others, atmospheric model intercomparison projects (AMIP) for AGCMs and coupled model intercomparison projects (CMIP) for AOGCMs (Meehl et al. 2005), both initiated by the World Climate Research Program (WCRP) and supported by the program for climate model diagnosis and intercomparison (PCMDI).[1] For example, within CMIP phase 3 (Meehl et al. 2007), coordinated climate projections of AOGCMs with interactive sea ice, based on emission scenarios from SRES, were prepared.

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[1] www-pcmdi.llnl.gov/projects/model_intercomparison.php.

Within CMIP phase 5 (Taylor et al. 2012), a new set of coordinated experiments of AOGCMs and ESMs, based on RCPs, has been established. The data are available via the earth system grid federation (ESGF) which can be accessed from several nodes world-wide.[2]

The first major effort on Europe-wide coordinated experiments with RCMs was the PRUDENCE project,[3] coordinated by the Danish Meteorological Institute and financed by the EU 5th framework program 2001–2004. This resulted in a series of climate change scenarios for 2071–2100 at a 0.5°–0.22° horizontal resolution for Europe (Christensen and Christensen 2007).

Within the later project ENSEMBLES,[4] coordinated by the Met Office Hadley Centre and financed by the 6th EU framework program 2004–2009, a coordinated matrix of global and regional model simulations, mainly for the SRES A1B scenario, was established for Europe at a 0.22° horizontal resolution (and for Africa at 0.44°) (Hewitt and Griggs 2004). The model data are freely available.[5]

Within the current worldwide initiative on coordinated downscaling experiments (CORDEX), a sample of the global climate simulations of CMIP5 were downscaled for most continental regions of the globe (Giorgi et al. 2009). The CORDEX datasets will be available via the ESGF. Some datasets are already accessible, others will follow successively.

Within the EURO-CORDEX initiative, a unique set of high resolution climate change simulations for Europe on a 0.11° horizontal resolution is currently established (Jacob et al. 2014). Around 26 dynamical downscaling experiments have been or will be conducted, mainly for the scenarios RCP4.5 and RCP8.5. It is possible to track the status of the simulations.[6] Datasets will also be available via the ESGF.

To estimate uncertainties in projections of future climate the multi-model ensemble approach has also been introduced in Earth system modelling of the North Sea region (e.g. Friocourt et al. 2012; Wakelin et al. 2012a; Bülow et al. 2014; Holt et al. 2014). Ensemble simulations sample global and regional model uncertainties, internal variability and potential but unknown greenhouse gas emissions, nutrient and carbon loads, and fishery scenarios (e.g. Meier et al. 2011b, 2012b; Wakelin et al. 2012a). An overview of recent model simulations for the North Sea is provided in Sect. A2.4.

A2.4 Regional Coupled Atmosphere–Ocean Model Simulations for the North Sea

For the assessment of regional climate change in the North Sea region, regional coupled atmosphere–ocean models are essential. They account for local topography and coastline, resolve mesoscale features of oceanic and atmospheric circulation, and are able to simulate small-scale air–sea coupling processes.

Changes in the hydrological system of coastal waters have been investigated within the German Federal Ministry of Transport, Building and Urban Development (BMVBS) research program KLIWAS task 2. The objective of subtask 2.01 'Climate Change Scenarios' is to generate reliable estimates of changes in atmospheric and oceanic conditions, with the help of suitable regional models. To date, simulations for the North Sea are mainly undertaken with regional atmosphere models and regional ocean models separately, which does not account for dynamic atmosphere–ocean interactions. The first coupled regional atmosphere–ocean models have been developed for the North Sea region (BfG 2013) within the activity KLIWAS[7] 'Coast' of the German Federal Maritime and Hydrographic Agency (BSH) in collaboration with the Max-Planck-Institute for Meteorology (MPI-M), the University of Hamburg (UH), the Climate Service Center Germany (GERICS) and the Swedish Meteorological and Hydrological Institute (SMHI).

The final KLIWAS report (Bülow et al. 2014) provides details and results of this activity. A short overview concerning the models and simulations follows. The regional ocean model HAMSOM (Pohlmann 2006) was coupled to the atmospheric model REMO (Su et al. 2014a). The ocean model of MPI, the global MPIOM, had previously been coupled to REMO in a similar way (Sein et al. 2015. A coupled model, comprising the atmospheric regional climate model RCA, and the regional ocean model NEMO, was applied by SMHI (Dieterich et al. 2013, 2014; Wang et al. 2015).

The coupled models were first validated with observed climate data for the past 30–50 years, by performing 'hindcast' simulations driven by reanalysis data. Atmosphere reanalyses data were from the National Center for Environmental Prediction (NCEP) or ERA-40 and ocean reanalysis data from the 'GECCO' data or from a climatology. The historical climate simulations and the climate

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[2] http://esgf-data.dkrz.de/esgf-web-fe/.

[3] http://prudence.dmi.dk/.

[4] www.ensembles-eu.org.

[5] http://ensemblesrt3.dmi.dk.

[6] www.euro-cordex.net/EURO-CORDEX-Simulations.1868.0.html.

[7] www.kliwas.de.

Table A2.1 Coupled and uncoupled simulations for KLIWAS 'Küste'. 'MPIOM-NS' denotes the coupling of the global MPIOM on the RCM domain (Mathis et al. 2013; Mathis and Pohlmann 2014)

Simulation	Global ocean	Global atmosphere	Regional ocean model	Regional atmosphere model	Coupling	Period
Hindcast	GECCO	NCEP	HAMSOM	–	No	1950–2000
Hindcast	Levitus climatology	ERA40	NEMO	RCA	No	1961–2002
Hindcast	MPIOM	NCEP	MPIOM-NS	–	No	1948–2007
Hindcast	MPIOM	NCEP	MPIOM-NS	REMO	Yes	1948–2007
Hindcast	MPIOM	NCEP	HAMSOM	REMO	Yes	1985–2000
Hindcast	MPIOM	NCEP	HAMSOM	REMO	No	1985–2000
Hindcast	NCEP/ERA40	NCEP	–	REMO	No	1958–2000
C20+A1B	MPIOM_r3	ECHAM5	NEMO	RCA	Yes	1950–2100
C20+A1B	MPIOM_r2	ECHAM5	NEMO	RCA	Yes	1950–2100
C20+A1B	MPIOM_r3	ECHAM5	HAMSOM	REMO	Yes	1950–2100
C20+A1B	MPIOM	ECHAM5	MPIOM	REMO	Yes	1920–2100
RCP4.5	MPIOM	ECHAM5	MPIOM-NS	REMO	Yes	1950–2100
RCP2.6	MPIOM	REMO	MPIOM-NS	REMO	Yes	1950–2100

projections based on the SRES A1B scenario were driven by global model data from ECHAM5/MPI-OM. A list of regional model simulations (coupled as well as uncoupled) performed within the KLIWAS project is given in Table A2.1.

Detailed information about models and analyses of simulation results are available via the German Federal Maritime and Hydrographic Agency website.[8] The final report of the KLIWAS Coast activity is also available (Bülow 2014).

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