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Annex 1: What is NAO?

Abdel Hannachi and Martin Stendel

The atmospheric circulation in the European/Atlantic sector, which also determines the regional climate of the North Sea region, can be described mainly by the North Atlantic Oscillation (NAO), the zonality or meridionality of the atmospheric flow and the frequency of atmospheric blocking. The NAO is the dominant mode of near-surface pressure variability over the North Atlantic Ocean and Europe, including the 'NOSCCA region', impacting a considerable part of the northern hemisphere (Hurrell et al. 2003). In its positive phase, the pressure difference between the two main centres of action—the Azores High and the Icelandic Low—is enhanced compared to the climatological average, resulting in a stronger than normal westerly air flow (Hurrell 1995). The storm-track extends north-eastward with more storms over the North Sea and northern Europe. These regions have therefore warmer and wetter than average conditions, especially during winter, whereas the Mediterranean region is generally drier and colder than normal. In contrast, during the negative phase of the NAO, the pressure difference between the Azores High and Icelandic Low is reduced, the storm track is more zonal and shifted southward, extending into the western Mediterranean, and the resulting air flow is weaker than normal (Xoplaki 2002; Xoplaki et al. 2004). For strongly negative NAO indices, the flow can even reverse when there is higher pressure over Iceland than over the Azores, with the consequence of harsh winters over large parts of Europe, such as occurred in 2009/2010 (Ouzeau et al. 2011). The strength of the NAO follows an annual cycle with maximum values in January and minimum values in May (Jones et al. 1997; Furevik and Nilsen 2005). Although the largest amplitude and explained variance occur in winter, the impact of the NAO on the North Sea region is present all year round.

Figure A1.1 shows the variability of the NAO over the past 190 years. From a long-term perspective, the behaviour of the NAO appears irregular. However, extended periods of positive or negative NAO indices are apparent. From the mid-1970s to the mid-1990s, positive index values prevailed (e.g. Hurrell et al. 2003). After the mid-1990s, however, there was a tendency towards more negative NAO indices, in other words a more meridional circulation, and it should be noted that the winter of 2010/2011 had the most negative NAO index in the record (Jung et al. 2011; Pinto and Raible 2012).

Fingerprints of the NAO have been known since at least the days of the Scandinavian sailors (Haine 2008), and from the mid-18th century it was noted (Egede 1745; Cranz 1765) that surface air temperatures in Greenland and Scandinavia vary in opposite phase (Stephenson et al. 2003; Pinto and Raible 2012). Depending on the season, the NAO pattern explains between 40 and 60 % of the total variance in sea-level pressure (SLP) over the North Atlantic Ocean (Wanner et al. 2001; Bojariu and Gimeno 2003; Hurrell et al. 2003).

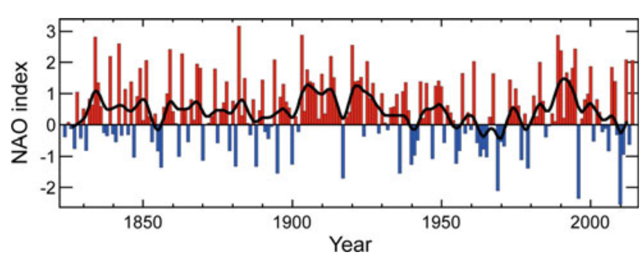

Fig. A1.1 North Atlantic Oscillation (NAO) index for boreal winter (DJFM) 1824/1825 to 2012/2013, calculated as the difference of the normalised station pressures of Iceland and Gibraltar (which is a good measure for the strength of the Azores High) from the monthly means of the period 1951–1980 (Jones et al. 1997, updated at www.cru.uea.ac.uk/~timo/datapages/naoi.htm). The *solid black line* is a 5-year running mean

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The North Atlantic sea-surface temperature (SST) responds to changes in large-scale atmospheric flow, particularly the NAO. For example, during positive NAO events, there is enhanced cooling of North Atlantic SST north of 45° N. The resulting negative SST anomaly affects air-sea interaction between about 30° and 45°N, leading to positive SST anomalies in this lower latitude band (Marshall et al. 2001). The correlation between the North Atlantic SST anomalies and the NAO index leads to a dipole pattern, known as the Bjerknes' North Atlantic SST dipole (Bjerknes 1962, 1964). The southern lobe of this dipole extends across the Atlantic to the North Sea and thus the NOSCCA region, where the correlation is at a maximum (see Visbeck et al. 2003: their Fig. 2). The NAO affects a whole spectrum of atmospheric and environmental processes, including tropospheric wind (Thompson et al. 2000; see also Fig. 2.2), precipitation (Lamb and Peppler 1987; Zorita et al. 1992; Hurrell and van Loon 1997), ocean surface characteristics (e.g. Moliarini et al. 1997), storminess (Rogers 1997; Serreze et al. 1997), North Atlantic/European atmospheric blocking frequency (Nakamura 1996; Woollings et al. 2010a, b; Häkkinen et al. 2011) and Sverdrup and Ekman transport (Visbeck et al. 2003).

Many approaches have been used to define the spatial structure of the NAO. Historically, (normalised) SLP differences between Iceland and Lisbon (Hurrell 1995), the Azores (Rogers 1997) or Gibraltar (Jones et al. 1997; Vinther et al. 2003) have been used. Several researchers use one-point correlation maps to identify regions of maximal negative correlation near or over Iceland and over the Azores extending to Portugal (e.g. Wallace and Gutzler 1981; Kushnir and Wallace 1989; Portis et al. 2001; Hurrell and Deser 2009). A related approach uses principal components and identifies the NAO by the eigenvectors of the cross-correlation matrix which is computed from the temporal variation of the grid point values of SLP, scaled by the amount of variance they explain (e.g. Barnston and Livezey 1987), or clustering techniques (e.g. Cassou and Terray 2001a,b). Several researchers use unrotated (Horel 1981; Thompson and Wallace 1998; Woollings et al. 2010b) or rotated empirical orthogonal functions (EOFs) (Cheng et al. 1995; Hannachi et al. 2007). Other techniques, such as NAO indices over latitudinal belts (e.g. Li and Wang 2003), optimally interpolated patterns, trend EOFs (Hannachi 2007a, 2008) and cluster analyses (Cheng and Wallace 1993; Kimoto and Ghil 1993; Hannachi 2007b, 2010) have also been proposed. Seasonality can also be taken into account by defining a seasonally and geographically varying NAO index (Portis et al. 2001). All these definitions lead to slightly different NAO indices; but the indices all resemble each other and are in fact highly correlated with each other (Leckebusch et al 2008).

All these definitions have in common that they are based on direct observations or analyses. However, it is also possible to use proxy data to extend the indices back in time. Several reconstructions exist that cover roughly the last millennium. These are based on early instrumental observations (Jones et al 1997; Luterbacher et al. 1999), ship logs (Küttel et al. 2009; Wheeler et al. 2009), other documentary data (Glaser et al. 1999; Luterbacher et al. 2001, 2004), climate field reconstructions (Jones and Mann 2004; Casty et al. 2007), ice cores (Appenzeller et al. 1998), speleothems (Trouet et al. 2009) or strontium/calcium ratios in coral (Goodkin et al. 2008). Multi-proxy reconstructions also exist, based on tree rings and snow accumulation records (Glueck and Stockton 2001) or on tree rings and stable isotope ratios (Cook et al. 2002).

A model-based reconstruction of past atmospheric circulation patterns is in principle possible. While climate models are able to capture the broad spatial and temporal features of the NAO (Gerber et al. 2008), the patterns of variability exhibit substantial differences between models and in comparison to observations (Xin et al. 2008; Casado and Pastor 2012; Handorf and Dethloff 2012). In particular, most models overestimate persistence on time scales from sub-seasonal to seasonal (Gerber et al. 2008). With few exceptions (Selten et al. 2004; Semenov et al. 2008), many climate models are unable to simulate the amplitude of changes in the observed NAO trend since the 1960s (Scaife et al. 2008, 2009; Stoner et al. 2009). This and the apparent underestimation of vertical coupling between troposphere and stratosphere in most models make it difficult to determine the extent to which the underestimation of trends is due to model deficiencies and the extent to which it mirrors anthropogenic forcing (Sigmond and Scinocca 2010; Karpechko and Manzini 2012; Scaife et al. 2012). Further uncertainties arise because there are indications that NAO variability may depend on the mean state of the atmosphere (Branstator and Selten 2009; Barnes and Polvani 2013). It has also been proposed that higher wave numbers could lead to resonance effects and therefore increased persistence of circulation regimes (Coumou et al. 2014), thus corroborating earlier findings, such as those by Kyselý and Huth (2006); see also Rutgersson et al. (2014). It remains an open question how far these drivers of NAO variability are related to changes in the Arctic, such as the decrease in sea ice.

A comparison of the different reconstructions can shed some light on the ability to reconstruct past atmospheric circulation patterns. Pinto and Raible (2012) made such a comparison (after applying a low-pass filter and normalisation) and found reasonable agreement between different reconstructions since the beginning of the 20th century, but also for a few periods in the more distant past (in particular between 1620 and 1720). As these studies rely on different numbers of proxies, different calibration methods and very different types of proxies, including growing-season data to estimate winter NAO, this is not unexpected (e.g. Schmutz et al. 2000). Furthermore, it is also unclear how valid the implicit assumption is that the relation between proxies and the NAO does not change over time.

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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.

[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

[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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[8]www.bsh.de/de/Meeresdaten/Beobachtungen/Klima-Anpassungen/index.jsp.

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Annex 3: Uncertainties in Climate Change Projections

Markku Rummukainen

A3.1 Introduction

The global emissions of carbon dioxide and other greenhouse gases change the atmospheric composition and enhance the natural greenhouse effect. The climate system responds by warming, sea-level rise, changing precipitation patterns, snow and ice melt, and so on. The overall nature, order of magnitude and many regional characteristics of this response are scientifically well-established. There are also unknowns and uncertainties, but these are not impenetrable. They can be studied in informative ways, which contributes to the utility of climate change projections. This annex provides a pragmatic overview of uncertainties in climate change projections including regional downscaling. The aim is to provide background for the discussion of climate models and climate change projections addressed by different chapters of this book.

A3.2 Climate Models and Climate Projections

Climate models are advanced simulation tools for the climate system, and its characteristics such as temperature, precipitation, clouds, winds, snow, waves, sea ice, ocean salinity, and so on. The basis for climate models is the collected scientific understanding of the fundamental physical, chemical and biological properties and processes of the climate system. The body of climate change projections is made with global climate models (GCM). The latest generation of such projections has been coordinated under CMIP5 (The Coupled Model Intercomparison Project Phase 5; Taylor et al. 2012). Regional climate models (RCMs) are the regional counterpart of GCMs, and are used for downscaling global model projections. For additional information on climate models see Annex 2.

There are three major reasons why climate models are the key scientific tool for making climate change projections. First, the full climate system is complex and its evolution does not lend itself to analytical or statistical representations. Second, the future climate cannot be observed. Third, the present anthropogenic climate forcing combined with the present-day climate baseline, is a unique development of the Earth's climate system.

When run with the present-day atmospheric composition of greenhouse gases, solar variability and land use, climate models simulate the present-day climate. Climate models are also used to model past and alternative future climates under external forcing scenarios, such as anthropogenic greenhouse gas emissions and land use change. It is important to note that all projections are conditional to their underlying assumptions and that specific projections apply for the specific forcing scenarios used, such as the assumed future greenhouse gas emissions.

As we do not know what the 'right' future emissions are, climate simulations are not 'predictions' in the same sense that we tend to view weather forecasts. Thus, the choice of emission scenario can be considered a source of uncertainty in climate projections. Possible major changes in natural climate forcing (solar variability, volcanic eruptions etc.) are another source of uncertainty, but they are not usually considered a climate *projection* uncertainty, since the projections concern climate change due to *anthropogenic* forcing.

A second source of uncertainty in climate projections is related to the different degrees of scientific understanding of climate system processes and to what level of detail they can be modelled with available computing resources. Climate models have different resolutions and differ in terms of how

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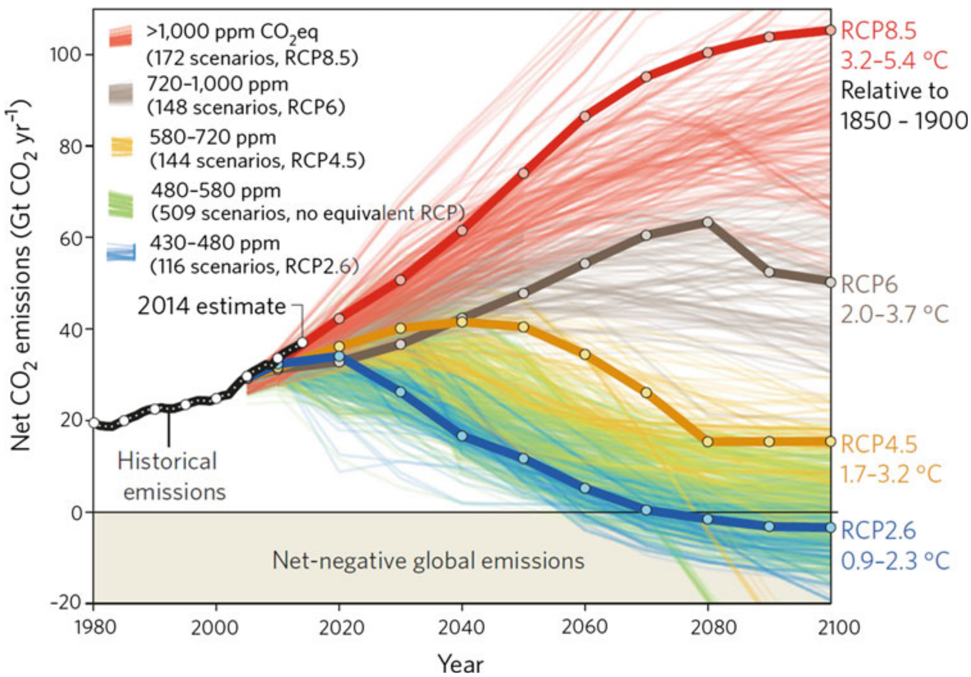

Fig. A3.1 Carbon dioxide emission pathways until 2100: historical emissions from fossil fuel combustion and industry (*black*), and from the early 2000s, possible future pathways based on emissions scenarios also used by the Intergovernmental Panel on Climate Change in its Fifth Assessment (Collins et al. 2013; Cubasch et al. 2013; IPCC 2013a). The Representative Concentration Pathways (RCP) are used in CMIP5 (Fuss et al. 2014). Reprinted by permission from Macmillan Publishers Ltd: Nature Climate Change 4, copyright 2014

climate processes are included and parameterised. This may affect their responses to forcing and lead to different climate models depicting smaller or larger changes compared to other models.

Internal variability is a third source of uncertainty in climate projections. It is created within and inherent to the climate system itself and arises, for example, from large-scale ocean–atmosphere interaction. On regional scales, internal variability is often larger than how it manifests itself in global mean quantities. For example, interannual temperature variability is larger on the scale of, say Europe, than in the global mean.

A3.3 Main Sources of Uncertainty

A3.3.1 Climate Forcing

Climate projections are conditional to their underlying emission scenarios (this is referred to as ‘emission uncertainty’). The higher the level of forcing, the greater the response of the climate system. As the ‘correct’ future emissions are yet unknown, the question of ‘how much will climate change’ becomes more like ‘if the emissions develop this way or that way, how much will climate change?’ This collapses the emission uncertainty into specific emission pathway alternatives, with the subsequent projection being specific to the particular emissions. However, as discussed below, such projections are still subject to other sources of uncertainty.

Climate projections are developed for a wide range of emission scenarios—from strong mitigation futures (low emission scenarios) to unabated emissions (high emission scenarios). Figure A3.1 illustrates the greenhouse gas emission pathways for a number of anthropogenic climate forcing scenarios (the four so-called RCP scenarios; Representative Concentration Pathways, see Moss et al. 2010. The ‘representative’ comes from the fact that they exemplify an even larger body of forcing scenarios from different studies; see the thick and thin lines in the graphic). The global CMIP5 climate projections are driven by these RCP-scenarios. It is not relevant here to describe in detail each of these scenarios, just to stress that each RCP implies a different amount of anthropogenic emissions and that they lead to rather different climate change outcomes for the medium term and even more so on longer time scales beyond the mid-21st century. Over the next couple of decades, anthropogenic emissions and thus atmospheric greenhouse gas levels are more or less already committed due to the existing energy-related infrastructure and investment flows, and land use change, etc. (e.g. Rummukainen 2015). In the longer term, both emission reductions and continued increases are in principle possible, depending on socio-economic developments (for example energy systems, technology, economic growth, policy, …). More information on emission scenarios is provided in Annex 4.

A3.3.2 Model Uncertainty

Climate models employ different resolutions, different numerical techniques and different parameterisations, and these are all sources of some uncertainty. For the purposes of this Annex, this is referred to as 'model uncertainty'.

The basic equations for the atmosphere and the ocean comprise a non-linear system. In climate models, the system of these equations is solved numerically. The solution is thus an approximation. Another issue is that climate system processes occupy a very wide range of spatial and temporal scales, and scale interactions are important. While larger scales can be explicitly simulated, phenomena that occur at scales smaller than the model resolution need to be expressed in terms of resolved large-scale features, that is, 'parameterised'. Examples of such processes are turbulence, convection and the influence of detailed surface characteristics. Also, parameterisations build on physical understanding. However, the complexity of the processes and interactions opens up different ways of describing a certain process. This leads to differences between climate models which may affect their climate sensitivity and subsequently projections.

A summary measure of this is the equilibrium climate sensitivity (ECS) which is defined as the long-term global mean temperature rise due to a doubling of carbon dioxide concentration in the atmosphere. The magnitude of climate sensitivity depends on the net effect of the various changes in the climate system due to warming. For example, a warmer atmosphere can hold more water vapour, which—being a greenhouse gas—enhances the warming (this is an example of a 'positive' feedback). Other key feedback is related, not least, to clouds. How these and other aspects of the climate system respond to emissions in the climate models varies to some extent for different parameterisations. For GCMs, climate sensitivity is not a predetermined parameter but is the combined effect of all processes represented within the models, and varies from about 2 °C to around 5 °C. For emission and atmospheric concentration scenarios other than a doubling of carbon dioxide concentration in the atmosphere, the range in the projected change in temperature will differ from that which corresponds to the equilibrium climate sensitivity.

A3.3.3 Internal Variability

Internal variability is an inherent characteristic of the climate system. Two well-known examples are the El Niño Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO). These are both intrinsic to the climate system even without external forcing. ENSO, for example, arises from the interplay between the atmosphere and the ocean. Analogous to the real system, climate models generate internal variability in the simulations, which can be compared to observed characteristics. However, climate models simulate *possible* courses of internal variability, whereas the real system follows the *actual* course. When a model is run many times with different initial conditions or other slight changes, the resulting simulations exhibit different courses of internal variability, while still possibly showing comparable climate statistics in terms of averages, trends and so on. This is embodied in the term *projection* (which is used instead of *prediction*).

Addressing internal variability is relevant both when evaluating climate models and when interpreting climate projections. For example, as the courses of internal variability differ in observations and models, the timing of NAO-phases (and their regional imprint on temperature and precipitation) can also differ. When comparing different climate projections, some of the difference in the projected changes may be because the models are in different internal variability states (Räisänen 2001). Internal variability can also mask—or enhance—climate change signals over some specific period. Successive changes relative to some reference period need to become sufficiently large before they become statistically distinguishable from historical climate variability (e.g. Kjellström et al. 2013).

A3.3.4 Relative Importance of Different Sources of Uncertainty

The relative importance of the climate forcing uncertainty, model uncertainty and internal variability varies with the time horizon and the spatial scale (e.g. Hawkins and Sutton 2009).

For the next few decades, the climate forcing uncertainty is small. This is because possible future emission pathways are not likely to diverge significantly over the short term. Also, because the impact of emissions unfolds with a delay, the past and present emissions will continue to affect the climate for some time to come. Towards the end of the 21st century, emission uncertainty typically becomes the largest contributor to climate projection uncertainty if the full range of global emission scenarios is considered. If some subset of emission scenarios is studied instead, for example very ambitious mitigation scenarios, other sources of uncertainty may govern the spread of results.

The relative importance of internal variability diminishes with time, as the climate change signal increases. The relative importance of internal variability is also smaller for global mean values than for regional projections. Thus, near-term regional climate projections may show fairly different results, depending on whether the simulated internal variability enhances or dampens the climate change signals (e.g. Kjellström et al. 2013).

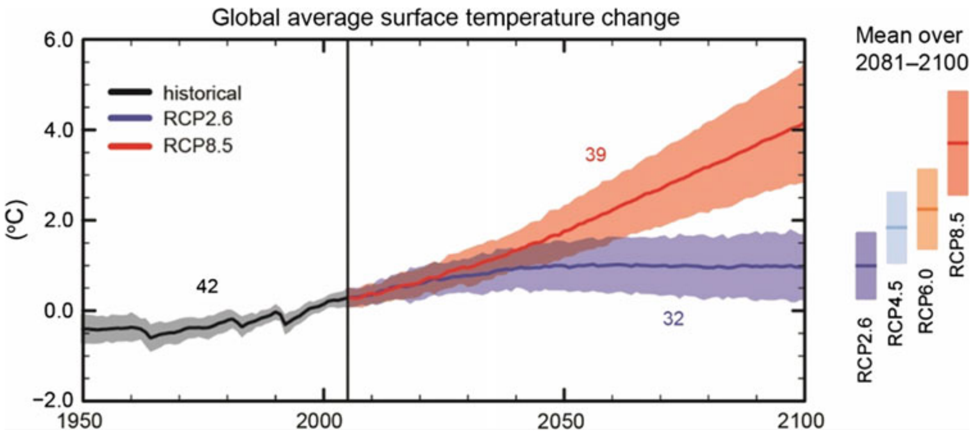

Fig. A3.2 CMIP5 multi-model simulated change in global annual mean surface temperature through the 21st century relative to present-day conditions (1986–2005). Time series of projections (*coloured lines*) and a measure of uncertainty (*shading*) are shown for scenarios corresponding to RCP2.6 (*blue*) and RCP8.5 (*red*). *Black* (*grey shading*) indicates the modelled historical evolution using historical reconstructed forcings. The numbers of CMIP5 models used to calculate the multi-model mean are also shown (IPCC 2013b: Fig. SPM.7, panel (a). Abridged caption)

Climate projections consistently show that anthropogenic greenhouse gas emissions lead to warming, sea level rise, etc., and that smaller (larger) emissions cause less (more) warming. Model uncertainty is nevertheless a factor to consider when assessing the magnitude of the changes and in some cases also the spatial patterns. The emission uncertainty, when considering a wide range of scenarios, catches up with the model uncertainty over time. This is illustrated in Fig. A3.2, where the envelopes show a measure for model uncertainty along high (red) and low (blue) emission scenarios.

A3.4 Quantifying and Qualifying Uncertainties

Climate models undergo continuous evaluation, not least by comparing simulations of the recent past and present-day climate to a range of observations (Räisänen 2006). Model intercomparisons provide additional information.

Overall, climate models simulate well many key aspects of the climate system, but there are also phenomena for which their performance is lower (Flato et al. 2013: e.g. Fig. 9.44). Models' performance also varies to some extent between regions, as is illustrated in Fig. A3.3. The models reproduce the large-scale features of global temperature and precipitation. The latest generation of GCMs have high pattern correlations with observations (0.99 for mean temperature and 0.82 for mean precipitation; Flato et al. 2013). In the case of temperature, relatively large model biases are nevertheless found in some coastal regions, close to sea ice edges, and in regions with major orographic features. In the case of precipitation, bias patterns are more varied. Biases can often be associated with specific physical phenomena (such as coastal temperature bias in upwelling regions) and/or resolution (such as the contrast in characteristics across the sea ice edge, or the lower resolution of orography in climate models than in reality).

Multi-model ensembles are a useful way to provide some quantification of uncertainties. While multi-model mean can be a useful indicator of trends, the spread of model results informs on uncertainty ranges due to internal variability and model uncertainties. A model can also be run a number of times with small variations to parameters in the parameterisations, within reasonable ranges, to gauge the significance of related model uncertainties (Murphy et al. 2004).

A3.5 Downscaling

The resolution of global models is typically lower than is desirable for climate impact studies and regional climate assessments. In regions with homogeneous physiographical features, or for large-scale time-averaged quantities, GCM-data may be sufficient as such or after interpolation. In many regions, however, while being conditioned by the large-scale conditions, local-to-regional climates are also significantly influenced by effects of variable land and ocean basin forms and heterogeneous surface characteristics. High resolution also facilitates simulation of small-scale temporal behaviour, such as extreme precipitation. RCMs are used for downscaling GCM output. This is also coined 'dynamical downscaling'. (Statistical downscaling is another method, but does not concern climate models.)

Dynamical downscaling extends information from global models with additional local-to-regional scale detail

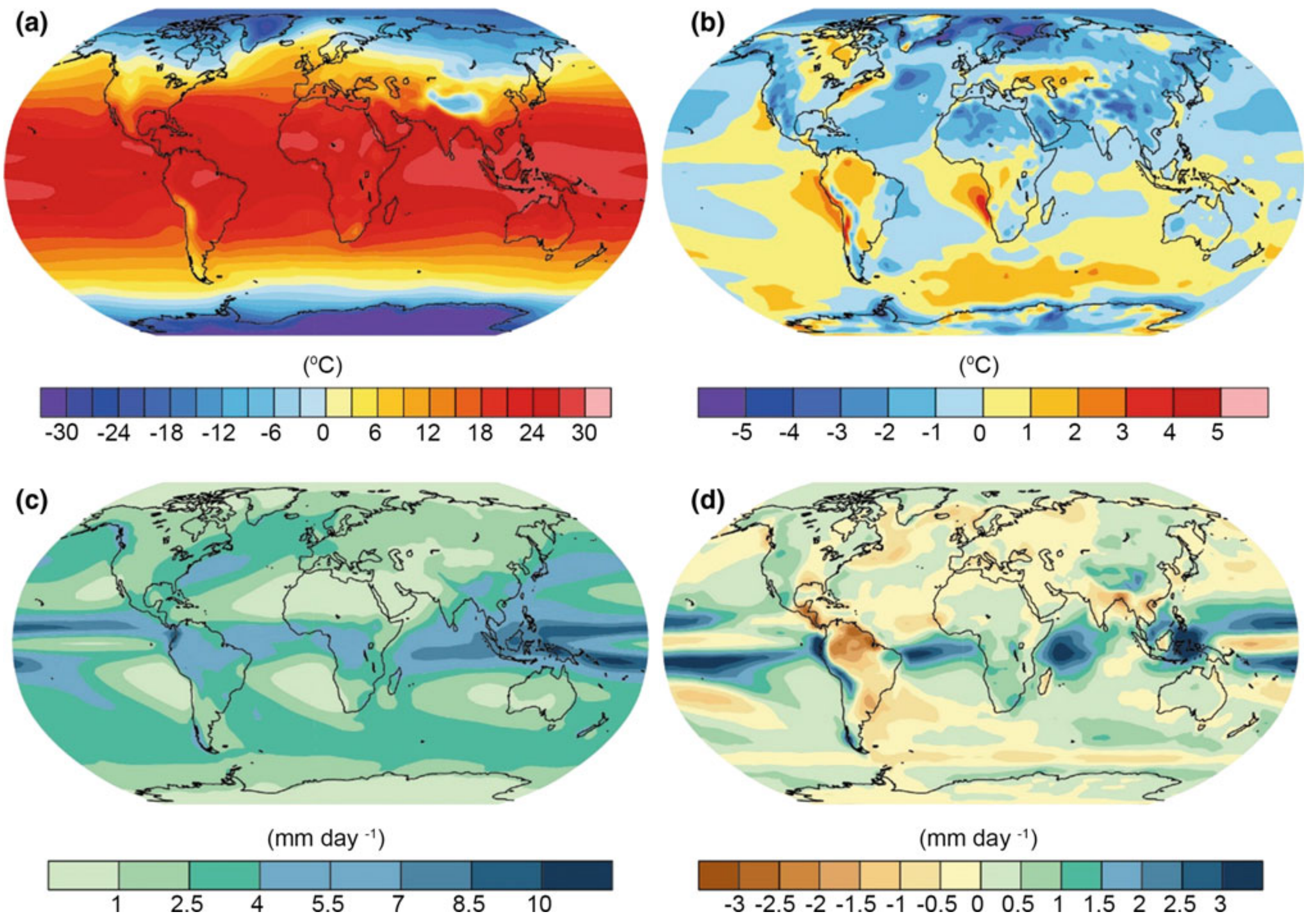

Fig. A3.3 Annual-mean surface (2-m) air temperature (°C) for the period 1980–2005: **a** multi-model mean for the CMIP5 experiment, **b** multi-model-mean bias as the difference between the CMIP5 multi-model mean and the climatology from ECMWF reanalysis of the global atmosphere and surface conditions (ERA)-Interim (Dee et al. 2011). Annual-mean precipitation rate (mm day^{-1}) for the period 1980–2005: **c** multi-model-mean in the CMIP5 experiment, **d** difference between multi-model mean and precipitation analyses from the Global Precipitation Climatology Project (Adler et al. 2003). Note the different scales for the respective mean and bias maps (Flato et al 2013: Figs. 9.2 and 9.4, panels (**a**) and (**b**). Abridged caption)

(Rummukainen 2010; Rockel 2015; Rummukainen 2016). Many RCMs feature an atmospheric and a land surface component, in which case sea-surface temperature and sea ice information is provided from the driving global model, which also provides the other boundary conditions for the regional model (see below). Regional interaction between the atmosphere and the ocean is not dynamic in such RCMs. There are, however, also regional ocean and coupled atmosphere–ocean RCMs (e.g. Döscher et al. 2002; Schrum et al. 2003), for example for the Baltic Sea, the North Sea, the Arctic Ocean and the Mediterranean Sea.

The same overarching sources of uncertainty apply for both global and regional climate models. An RCM covers a specific limited area domain (cf. Fig. A3.4). RCMs feature the same basic equations as GCMs, and are thus subject to emission uncertainty and model uncertainty, and generate internal variability. In terms of projections, RCMs are also affected by their boundary conditions, that is, the GCMs that are being downscaled. In a way, GCM uncertainty could be likened to emission uncertainty in the sense that a particular RCM projection is conditional to the choice of the emission scenario and the boundary conditions. The latter comprise large-scale inflow and outflow (winds, temperature, humidity) into and from the regional domain, from the driving GCM. RCMs can also be provided with boundary conditions from global reanalyses (e.g. Dee et al. 2011), which is often the case in model evaluation studies as comparison with actual observations is more straightforward than in the case of runs with boundary conditions from GCMs.

A key motivation of RCMs is that they facilitate simulations at higher resolution. Today, RCMs are starting to provide climate simulations at resolutions of 1–10 km, compared to around 25 km some 5–10 years ago, and 50 km or more some 10–15 years ago.

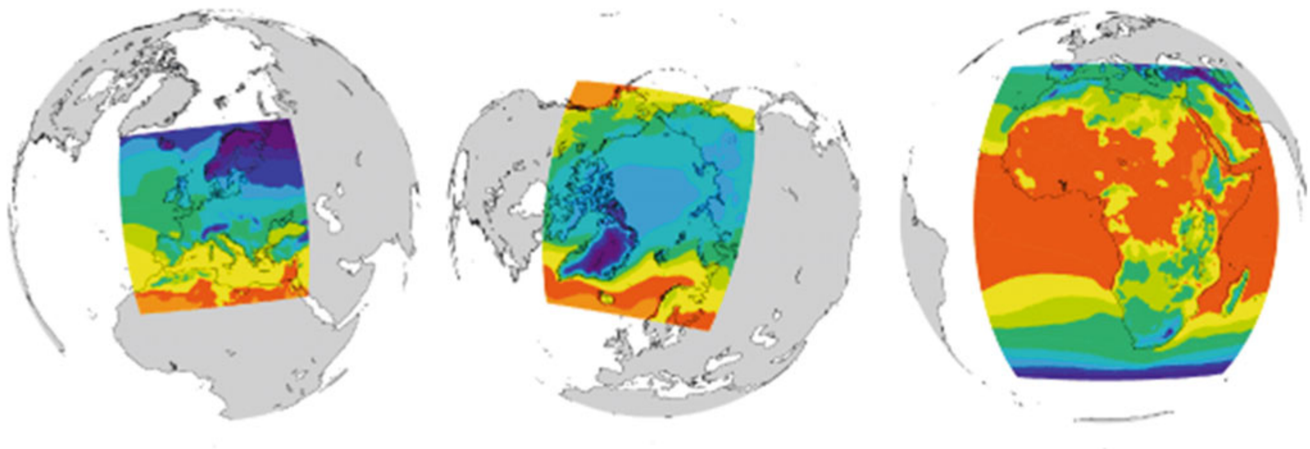

Fig. A3.4 Three examples of a regional climate model domain; for Europe, the Arctic region and Africa. The colours indicate simulated temperature climate. Figure courtesy of the Swedish Meteorological and Hydrological Institute (SMHI)

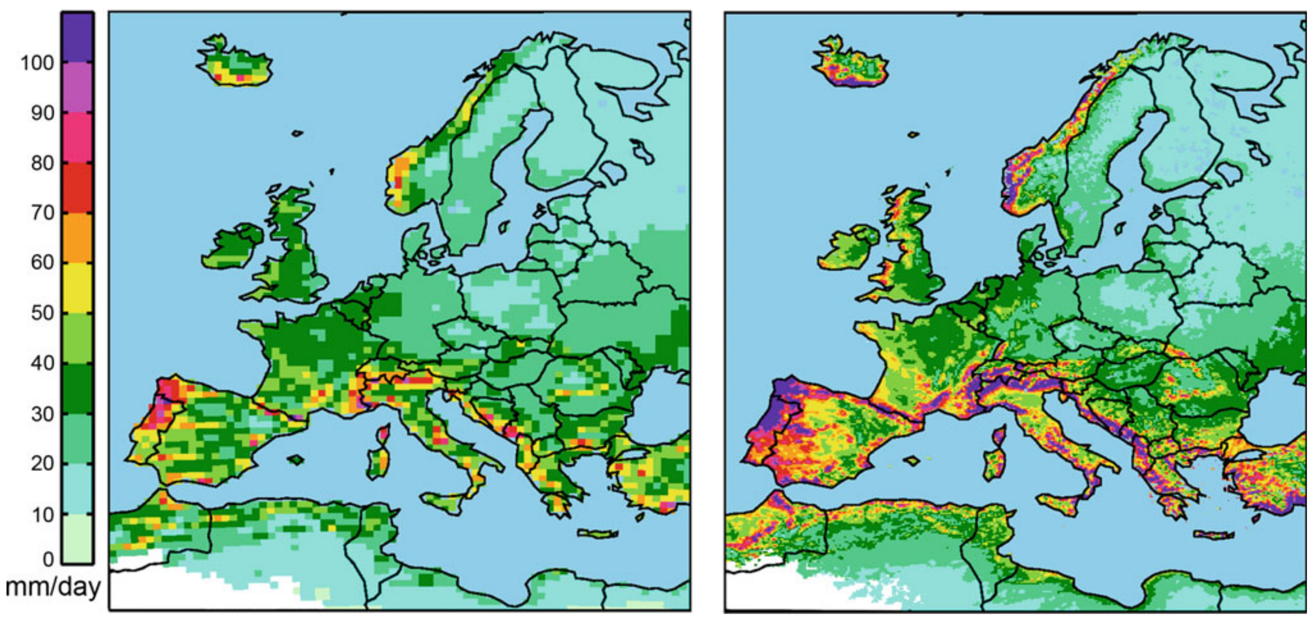

Fig. A3.5 Simulated precipitation intensity with a 20-year return period in winter and for 1971–2000 from a 50-km RCM run (*left*) and a 12-km RCM run (*right*). Differences are evident along many coastlines and in regions of variable orography. Figure courtesy of SMHI

Compared to GCMs, in RCMs extremes can be studied more explicitly, geographical detail resolved better (consider an extreme case of a coarse resolution model for the Nordic region; would it be better to wholly open up the connection between the Baltic Sea and the North Sea by removing Denmark, or totally close off the Baltic Sea?) and suchlike. Figure A3.5 provides an illustrative example of how geographical patterns of extreme precipitation may be simulated in an RCM at two different resolutions. Precipitation patterns and amounts are positively affected, for example, in mountainous regions and along western coastlines.

Figure A3.6 shows an example of RCM projections, for wintertime warming in Europe. Here, a specific RCM has been used to downscale three projections from one GCM which has been run with three different emission scenarios. In all cases, the warming increases with time (compare the panels in each row from left to right), and is greatest towards the north-east. Larger emissions cause greater warming (compare the rows in each column). An indication of internal variability is evident not least in the first two columns. Even though the recent past and near-future emissions are comparable, the regional temperature changes differ. Here, internal variability either enhances or reduces the long-term

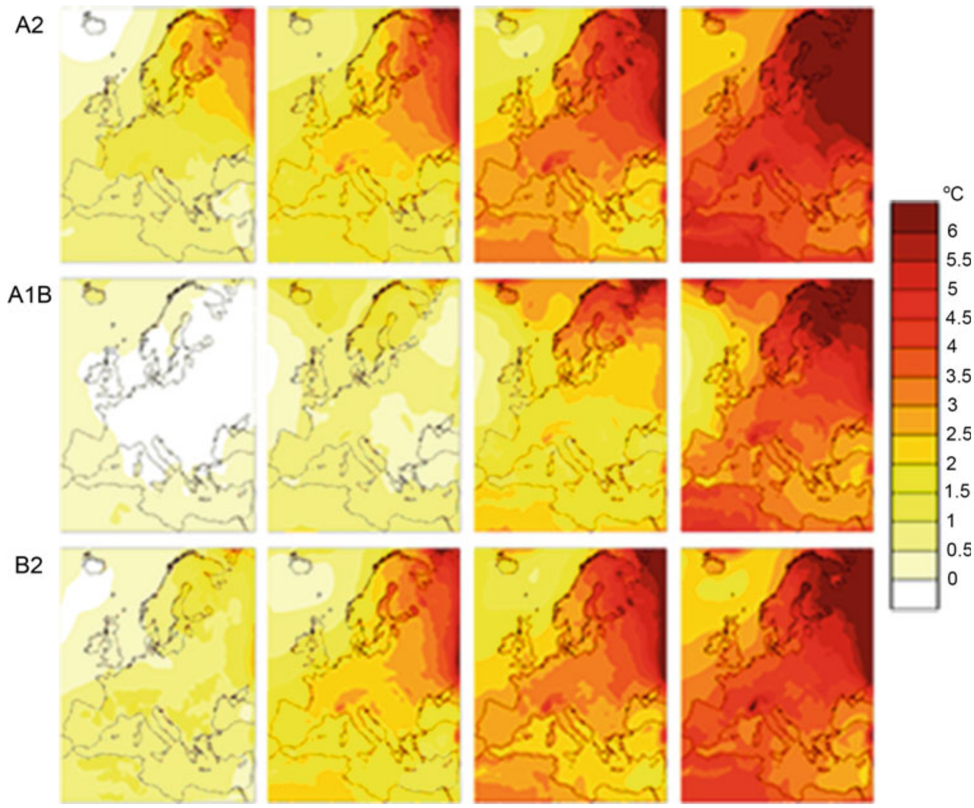

Fig. A3.6 Projected winter season (DJF) temperature increase (°C) for Europe under three emission scenarios (among these, the greenhouse gas emissions are largest for the SRES A2 scenario and lowest for the SRES B2 scenario; these are from an earlier scenario compilation compared to the RCPs). The same global climate model (GCM) and regional climate model (RCM) are used in all cases. The columns depict, from left to right, projections for the thirty-year periods 1981–2010, 2011–2040, 2041–2070 and 2071–2100, compared to 1961–1990. Based on Kjellström et al. (2005)

trend, depending on the particular projection. With time, the warming increases and its magnitude surpasses the internal variability amplitude, after which the differences between the projections are primarily governed by emission scenarios.

The choice of GCM also matters. If the RCM and the emission scenario are the same, differences between regional projections should be due to the choice of GCM (including its climate sensitivity, internal variability and possible model biases), and internal variability generated in the RCM. For large forcing, the latter can be expected to be small especially for temperature change. For other aspects, such as precipitation and wind, it may still be considerable, if the forced change is small and/or the phenomenon is characterised by large variability, such as extreme winds.

Figure A3.7 shows regional temperature and precipitation projections for the Baltic Sea region for the early, mid- and late 21st century, based on data both directly from GCMs and after their downscaling with an RCM. Temperature changes on this scale are comparable between GCMs and RCMs. The same applies for precipitation in winter for this region, but less so in summer. For the latter, the precipitation change in the GCMs varies from decreases to increases, whereas the range after downscaling is from no change to increases. There is also a tendency for larger (smaller) changes after downscaling than the direct GCM results in winter (summer).

A3.6 Discussion and Conclusion

All models and all observations are subject to some uncertainty, whether this is due to limitations in understanding, the instrument, model or experimental design, or some other reason. However, these uncertainties can be understood and communicated in ways that both highlight the robust knowledge and inform usefully on its limitations.

Climate models are the primary means for acquiring scientifically sound information on alternative future climates. Climate projections have utility, but also uncertainties. Uncertainties are, however, bounded and can be studied and characterised in informative ways. Continued climate system observations (such as on the deep ocean heat content) and increasing computing capacity (to allow for increased model resolution, larger model ensembles, incorporation of new model components) can contribute to reducing these uncertainties. Nevertheless, climate projection uncertainty will never be reduced to zero. Even if climate models were perfect depictions of the climate system, uncertainty related to climate forcing, i.e. the future emissions, would still persist. Also, there is no reason to expect that the time evolution of simulated internal variability should match the observed one other than statistically.

In terms of long-term global climate projections, uncertainty on future emissions is of primary importance. Larger

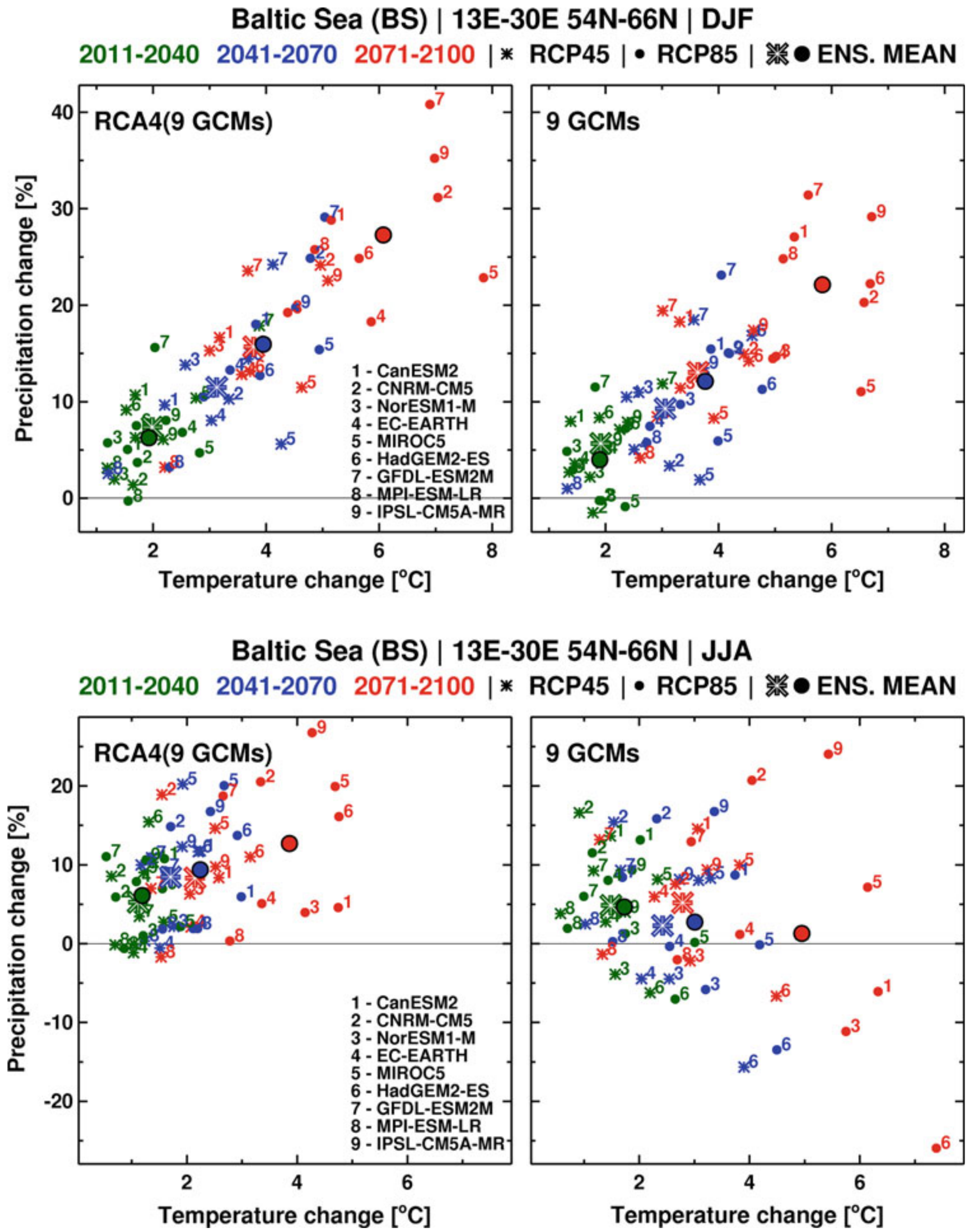

Fig. A3.7 Results from nine GCMs (*right-hand panels*; the numbers identify the GCMs) and after downscaling with the Swedish RCA4 regional climate model (*left-hand panels*). The plots show projected winter (DJF, *upper*) and summer (JJA, *lower*) precipitation and temperature changes for the Baltic Sea region as a whole. Two different climate forcing scenarios (RCP4.5 and RCP8.5) underlie these projections. They are identified by different symbols as depicted at the top of the panel. The colours indicate results for successive 30-year periods during the 21st century. The large symbols correspond to the GCM and RCM ensemble means, in the respective plots. Figure courtesy of SMHI

emissions lead to larger changes and smaller emissions to smaller changes. But how large and, respectively, how small, is subject to model uncertainty, i.e. how well relevant climate processes are represented. For the near-term, uncertainty related to internal variability can be comparable to model uncertainty, whereas emission uncertainty is small. Internal variability becomes less of a concern with increasing projection time horizon (i.e. mounting cumulative emissions), especially at a global scale.

Downscaling inherits uncertainties already present in the driving global model and the underlying emission scenario. Downscaling can, however, improve the projections by taking into account the effect of topography on near-surface climate phenomena, which in many cases is relevant for temporal and spatial information, for example in regions and at scales on which orography and land-sea distribution is important. Downscaling is also useful for studying phenomena with high spatial and/or temporal resolution, such as precipitation extremes.

Uncertainties in climate change projections need to be studied, characterised and managed. Although use of single projections can provide an example of alternative possible future conditions in an application, it is generally advisable to use results from many climate models in climate scenario analysis or impact assessment. This makes it possible to highlight robust outcomes as well as to identify results that should be considered more uncertain. A further alternative to the use of many single scenarios can be the generation of probabilistic projections, such as ensemble means and spreads, for applications which have the possibility to use such information.

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Annex 4: Emission Scenarios for Climate Projections

Markus Quante and Christian Bjørnæs

A4.1 Introduction

Comprehensive climate models are the main tools for projecting future changes in climate (see Annex 2). They are used to develop scenarios for potential climate change impacts which then provide the basis for mitigation and adaptation strategies. Climate projections depend strongly on the underlying assumptions concerning future greenhouse gas (GHG) and particle emissions or their respective precursor gases and are subject to model uncertainties. The latter are addressed in Annex 3. This Annex describes the emission scenarios used by the Intergovernmental Panel on Climate Change (IPCC) in its last three climate change assessments. These scenarios are also relevant to many of the results discussed in this assessment of climate change in the North Sea region.

A scenario is a description of potential future conditions produced to inform decision-making under uncertainty. In addition to a reliable model of the physical climate system, projections of future climate require estimates of the development of forcing agents. Variations in mid-term natural external forcing agents such as incoming solar radiation and volcanic activity are known, at least to some extent, for the past centuries and can be used in model simulations of the past climate. However, their future variability cannot be known because their behaviour is largely unpredictable. Nevertheless, their recent magnitude is less than the present-day human impact on climate. Although future anthropogenic external forcings via GHG emissions and changes in land use are also unknown, their historical growth, present-day magnitude and likely near-future trend are well established, and their longer-term development, such as over the 21st century can be estimated using assumptions concerning global socio-economic developments. As the underlying future GHG emissions will depend on economic, social and political trends that cannot be predicted because they are determined by decisions that have not yet been taken, emission scenarios comprise a wide range of assumptions on the future development of humankind. However, decision-making can narrow the assumptions, if for example, ambitious mitigation developments are chosen.

Thus, scenarios are descriptions of different possible futures, a series of alternative visions of futures (storylines) which are possible, plausible, and internally consistent but none of which is necessarily probable (von Storch 2008). The possibility that any single emission path will occur as described in scenarios is highly uncertain. Because many of the underlying factors are difficult or impossible to predict, a variety of assumptions must necessarily be used in the scenarios. And because emission scenarios for climate change research reflect expert judgements, it is no surprise that some of those expert judgements have been challenged by colleagues (e.g. Pielke et al. 2008).

Early approaches in the assessment of future climate change based on comprehensive general circulation models (GCMs) used a doubling or quadrupling of the pre-industrial carbon dioxide (CO_2) concentration as the driver for so-called equilibrium runs. Simulations using simple time-dependent transient scenarios, such as a steady (for example) 1 or 2 % increase in the atmospheric GHG concentration over the period under consideration, came next. The IPCC-related modelling studies associated with its 1990 assessment started to build on transient emission pathways that played out uncertainties in population and economic

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Table A4.1 Brief description of the SRES 'A' and 'B' storylines (after IPCC 2001)

Scenario	Description
A1	A world of rapid economic growth and rapid introduction of new and more efficient technology. The A1 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income
A2	The A2 storyline and scenario family describes a very heterogeneous world with an emphasis on family values and local traditions (high-CO_2). The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing population. Economic development is primarily regionally orientated and per capita economic growth and technological change is more fragmented and slower than other storylines
B1	A world of 'dematerialisation' and introduction of clean technologies (low-CO_2). The B1 storyline and scenario family describes a convergent world with the same global population, that peaks in mid-century and declines thereafter, as in the A1 storyline, but with rapid change in economic structures toward a service and information economy, with reductions in material intensity and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social and environmental sustainability, including improved equity, but without additional climate initiatives
B2	A world with an emphasis on local solutions to economic and environmental sustainability. It is a world with continuously increasing global population, at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also orientated towards environmental protection and social equity, it focuses on local and regional levels

growth as well as different technological futures. See Moss et al. (2010) for a short historical delineation of the development of scenarios for use in climate change research.

The present text focuses on scenarios used by the IPCC in its assessment reports released between 2001 and 2014 (IPCC Third Assessment Report, TAR; IPCC Fourth Assessment Report, AR4; IPCC Fifth Assessment Report, AR5; as well as special reports) as they cover the majority of scenario-driven climate change and impact studies reported in the various chapters of the present assessment. A dedicated activity to build the scenarios used in TAR and AR4 resulted in the so-called *Special Report on Emission Scenarios* (SRES) (IPCC 2000). The latest set of scenarios, used in AR5, followed a new approach for scenario development that uses so-called representative concentration pathways (RCPs) of future forcing and in parallel (or as a follow-up process) examined the range of socio-economic assumptions in model runs consistent with the RCPs, sharing during this step prior experience in the use of narratives and scenarios (Moss et al. 2010; van Vuuren et al. 2011a).

The remainder of this annex draws on material from Quante (2010), Bjørnæs (2013) and WGBU (2014).

A4.2 SRES Scenarios

The IPCC generated three sets of 21st-century GHG emission scenarios, of which the most ambitious and important were produced for the *Special Report on Emissions Scenarios* (IPCC 2000). The SRES Report uses 40 alternative scenarios which differ in terms of their assumptions about the future development of global society. Of these 40 scenarios, which are based on a comprehensive literature review and designed to depict most of the variation in their underlying drivers, the IPCC developed four qualitative storylines for which six 'marker' scenarios were created. One quantification of each storyline was produced plus two technological variants that stressed fossil-intensive and low-carbon energy supply technologies. Related uncertainties in future GHG and short-lived pollutant emissions including sulphur dioxide (SO_2), an important precursor for atmospheric sulphate particles, led to a wide range of driving forces.

The narrative storylines were developed so as to describe consistently the relationships between emission driving forces and their evolution. The scenario groups are known as A1, A2, B1 and B2, each based on diverse assumptions about the factors driving the development of human society through the 21st century. They thus represent different demographic, social, economic, technological, and environmental developments. In general, in the world described by the 'A storylines' people strive for personal wealth rather than environmental quality. In the 'B storylines', by contrast, sustainable development is pursued. However, the SRES scenarios do not include additional climate initiatives, which means that no scenarios are included that explicitly assume implementation of the United Nations Framework Convention on Climate Change or the emissions targets of the Kyoto Protocol. That is, the scenarios do not anticipate any specific mitigation policies for avoiding climate change. The scenario families are characterised in Table A4.1

Illustrative scenarios were chosen for each of the scenario groups A1, A2, B1 and B2, with A1 scenarios split into three distinguishable sub-classes. The A1FI, A1T and A1B illustrative scenarios describe alternative directions of technological change in the energy system, and are therefore quite different in terms of GHG emissions. In A1FI, energy production remains highly dependent on fossil fuels throughout

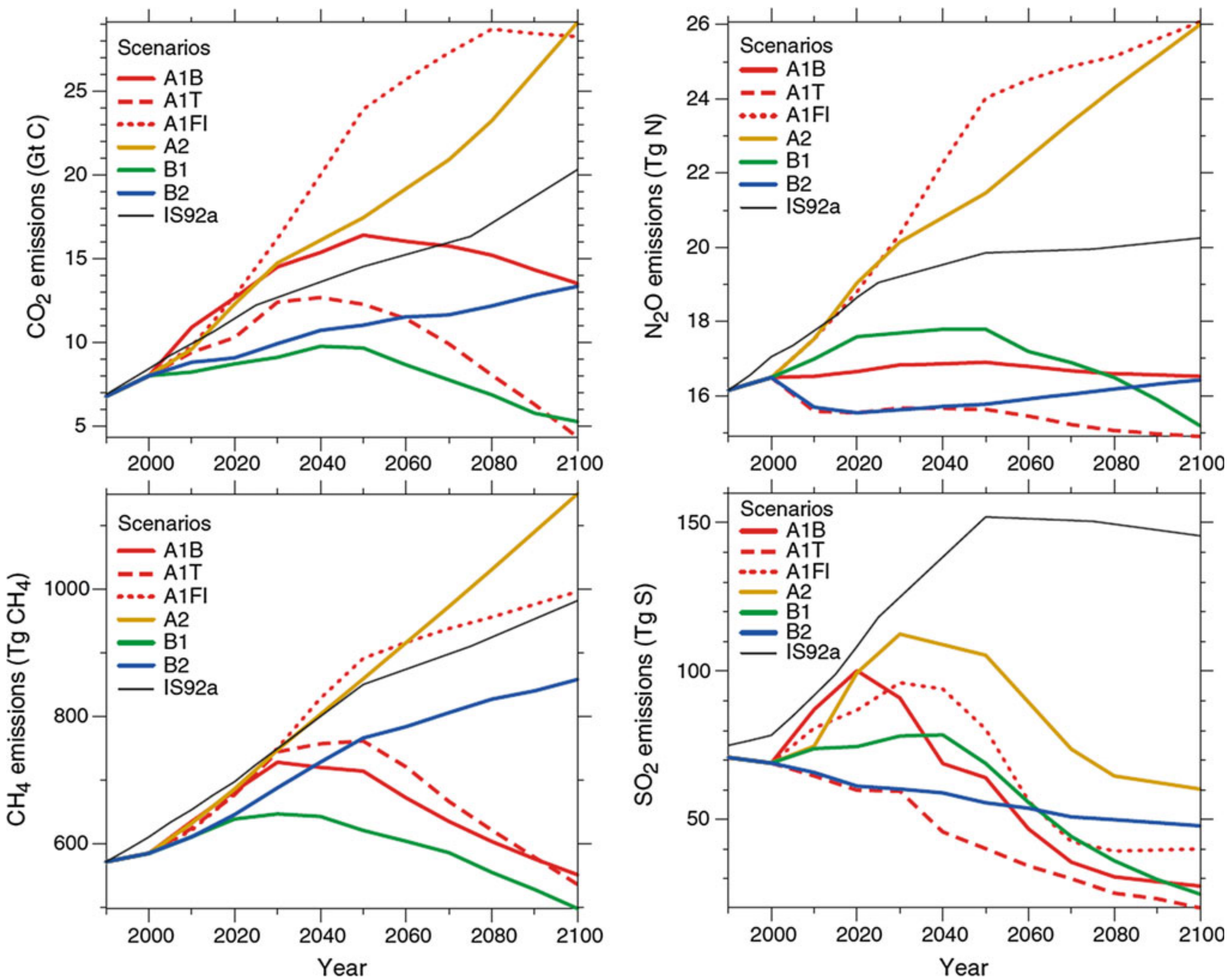


Fig. A4.1 Anthropogenic emissions of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and sulphur dioxide (SO_2) for the six illustrative SRES scenarios, A1B, A2, B1 and B2, A1FI and A1T. One of the scenarios used for projections made in the 1990s (IS92a) is also shown for comparison (IPCC 2000)

the century, whereas A1T represents a rapid migration toward non-fossil energy sources and incorporates the use of advanced technologies. A1B is intermediate between these extreme cases (not relying too heavily on one particular energy source and similar improvement rates for all energy supply and end-use technologies). Of these, A2, A1B and B2 scenarios have been widely used in climate modelling. Figure A4.1 shows the emission time lines of major GHGs and of the sulphate aerosol precursor gas SO_2 aligned with the different SRES scenarios for the 21st century. The increasing spread of the emission curves with time underlines the broadness of the underlying economic and technological developments driving the scenarios. For CO_2 emissions, A2 and B2 show a steady increase throughout the 21st century, A1F1 shows a strong increase until 2080 and then a slight decline, and A1B, A1T and B1 show a decline from around mid-century.

None of the SRES scenarios in the set includes any future policies that explicitly address climate change, an aspect criticised by social scientists. This type of criticism as well as new economic data, new views about emerging technologies and land use and land cover change, called for the development of a new set of scenarios starting just after the release of AR4 in 2007 (Moss et al. 2008). The newest scenarios are the subject of the following section.

A4.3 RCP Scenarios

The SRES scenarios were developed along a sequentially linear chain that started with different socio-economic futures followed by an estimation of related GHG and particle emissions which were converted to concentrations and radiative forcings. Either of the latter could serve as the

Table A4.2 Brief description of the selected RCPs

Pathway	Description
RCP8.5	A high emission pathway for which radiative forcing reaches more than 8.5 Wm^{-2} by 2100 and continues to rise thereafter. This RCP is consistent with a future with no additional policy changes to reduce emissions and is characterised by rising GHG emissions. (The corresponding ECP assuming constant emissions after 2100 and constant concentrations after 2250) (developed by the International Institute for Applied System Analysis in Austria; Riahi et al. 2011)
RCP6.0	Intermediate stabilisation pathway in which radiative forcing is stabilised at approximately 6.0 Wm^{-2} after 2100 through the application of a range of technologies and strategies for reducing GHG emissions. (The corresponding ECP assuming constant concentrations after 2150) (developed by the National Institute for Environmental Studies in Japan; Masui et al. 2011)
RCP4.5	Intermediate stabilisation pathway in which radiative forcing is stabilised at approximately 4.5 Wm^{-2} after 2100 through relatively ambitious emissions reductions. (The corresponding ECP assuming constant concentrations after 2150) (developed by the Pacific Northwest National Laboratory in the USA; Thomson et al. 2011)
RCP2.6	A pathway where radiative forcing peaks at approximately 3 Wm^{-2} before 2030 and then declines to 2.6 Wm^{-2} by 2100. This scenario is also called RCP3-PD (peak and decline). To reach such forcing levels, ambitious GHG emissions reductions would be required over time. (The corresponding ECP is assuming constant emissions after 2100) (developed by PBL Netherlands Environmental Assessment Agency; van Vuuren et al. 2011b)

The references indicate articles that describe the respective RCP-scenario in full detail. The Extended Concentration Pathways (ECPs) cover the period 2100–2300 and are described by Meinshausen et al. (2011)

driver for climate model studies. This sequential approach was seen as a reason for delay in the process as a whole: from scenario generation to climate modelling to climate impact studies.

To shorten the process an alternative parallel approach was developed. This resulted in the so-called representative concentration pathways (RCPs). RCPs represent a different approach to scenario development, one that recognises that many scenarios of socio-economic and technological development can lead to the same pathways of radiative forcing (changes in the balance of incoming and outgoing radiation to the atmosphere caused by changes in the concentrations of atmospheric constituents). Selecting a few RCPs as examples (seen as 'representative') allows researchers to develop scenarios for the different ways the world might achieve those RCPs and to consider the consequences of climate change when those RCPs are achieved via specific scenarios. The word 'pathway' indicates that not only are the values in a reference year (i.e. 2100) of interest but also the trajectory over time. This approach is intended to increase research coordination and simultaneously to reduce the time needed to generate useful scenarios. Climate modelling studies and impact studies can already be conducted before a full set of socio-economic information is available (van Vuuren and Carter 2014).

In a parallel process to climate modelling and impact studies, the scenario community has used Integrated Assessment Models (IAMs) to develop a set of consistent technological, socio-economic and policy scenarios with storylines that could lead to particular concentration pathways (van Vuuren et al. 2011a). These so-called shared socio-economic pathways (SSPs) are intended to guide mitigation, adaptation, and mitigation analysis (O'Neill et al. 2014; van Vuuren and Carter 2014).

The SSPs enable researchers to test various permutations of climate policies and social, technological, and economic circumstances. For example, at a global scale, higher population or increased energy consumption could be compensated by a higher fraction of renewable energy. So rather than prescribing economic development and calculating climate change, researchers could pick an RCP scenario that is compatible with the 2 °C target, for example, and then assess various technology and policy options for achieving the emissions consistent with that pathway and target.

More specifically, RCPs are time and space-dependent trajectories of concentrations of GHGs and pollutants resulting from human activities, including changes in land use. RCPs provide a quantitative description of concentrations of the climate change pollutants in the atmosphere over time, as well as their radiative forcing. One of the goals was to reduce the number of scenarios to a manageable number showing an adequate separation of the radiative forcing pathways at the end of the specified time horizon (Moss et al. 2010). Candidate scenarios were chosen after a thorough selection from the large stock available in the peer-reviewed literature. The eventual selection was four scenarios: RCP2.6, RCP4.5, RCP6.0, and RCP8.5 (see Table A4.2). The RCPs are named to highlight the radiative forcing they achieve in 2100; for example, RCP6.0 achieves 6 Wm^{-2} by 2100.

The GHGs included in the RCPs are CO_2, methane (CH_4), nitrous oxide (N_2O), several groups of fluorocarbons (halogenated) and sulphur hexafluoride. The aerosols and chemically active gases are SO_2, black carbon, organic carbon, carbon monoxide, nitrogen oxides, volatile organic compounds, and ammonia. For the resulting scenarios, Fig. A4.2 shows the development of radiative forcing through the 21st century and attributes the forcing at 2100 among the GHGs.

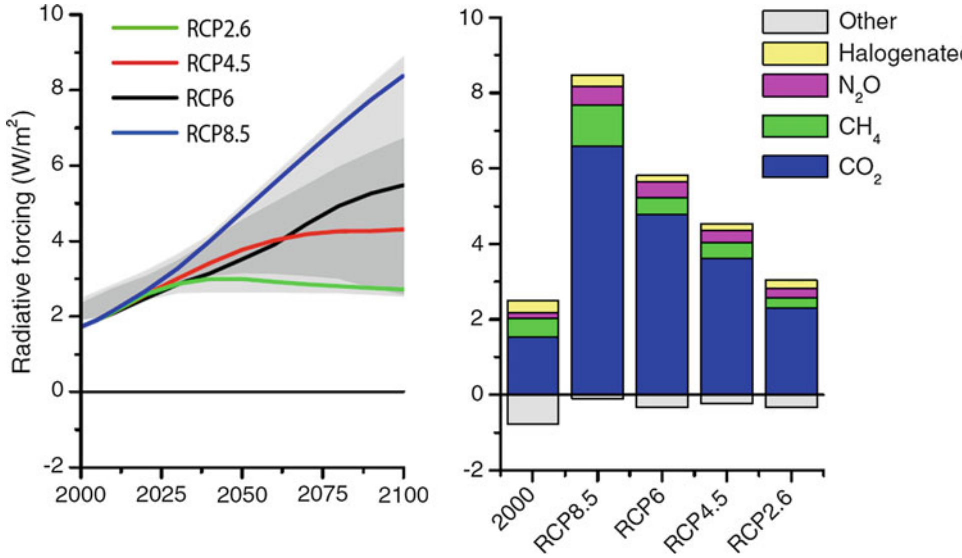


Fig. A4.2 Trends in radiative forcing (*left*) and 2100 forcing level per category (*right*). Forcing is relative to pre-industrial values and does not include land use (albedo), dust, or nitrate aerosol forcing (van Vuuren et al. 2011a)

Table A4.3 Major features of the selected RCP scenarios (after Moss et al. 2010)

RCP	Radiative forcing in 2100 (Wm^{-2})	CO_2 equivalent concentration in 2100 (ppm)	Type of change in radiative forcing
RCP8.5	>8.5	>1370	Rising
RCP6.0	~6.0	~850	Stabilising without overshoot
RCP4.5	~4.5	~650	Stabilising without overshoot
RCP2.6	~2.6 (peak at ~3 Wm^{-2} before 2100)	~450 (peak ~490 ppm before 2100)	Peak and decline

See Moss et al. (2010) and van Vuuren et al. (2011a) for more details of the scenario-building process and resulting scenarios. The main characteristics of the selected RCPs are listed in Table A4.2, while Table A4.3 provides a quick overview of major features.

For the well-mixed GHGs, the emissions and concentrations were harmonised using an IAM (Meinshausen et al. 2011). The emission trends for the four scenarios are given in Fig. A4.3 and the corresponding concentrations are shown in Fig. A4.4. The different developments of the emission and concentration trends are obvious. A striking result is that towards the end of the century for RCP2.6 negative CO_2 emissions occur. RCP2.6 is the only RCP scenario with the potential to meet the so-called 2 °C limit to global warming.

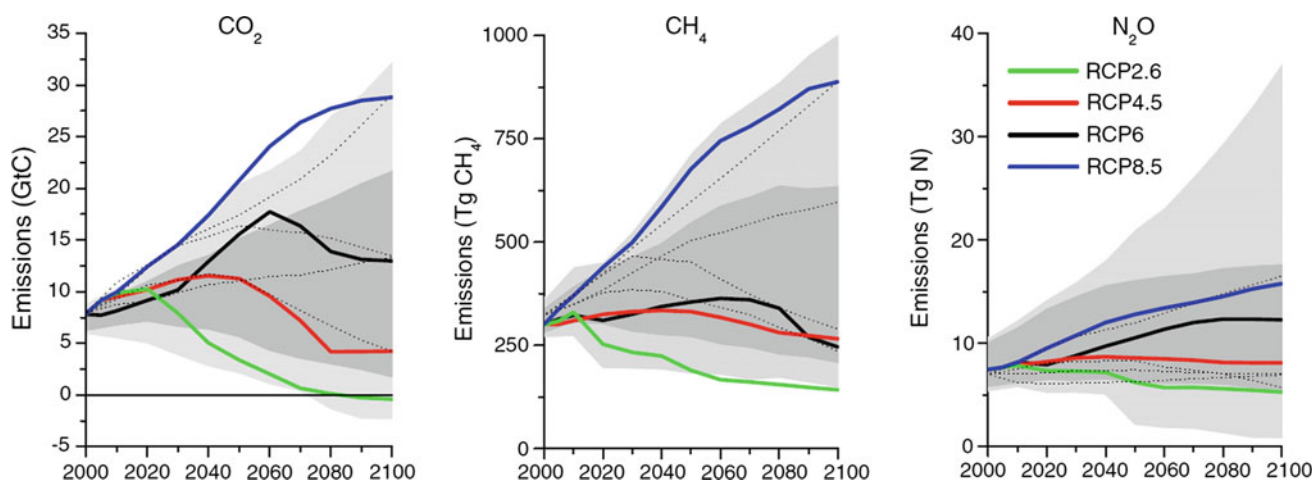


Fig. A4.3 Emissions of the main greenhouse gases carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) across the RCPs. The *grey area* indicates the 98th and 90th percentiles (*light/dark grey*) of the underlying scenarios from a literature survey. The *dotted lines* indicate four SRES marker scenarios (van Vuuren et al. 2011a)

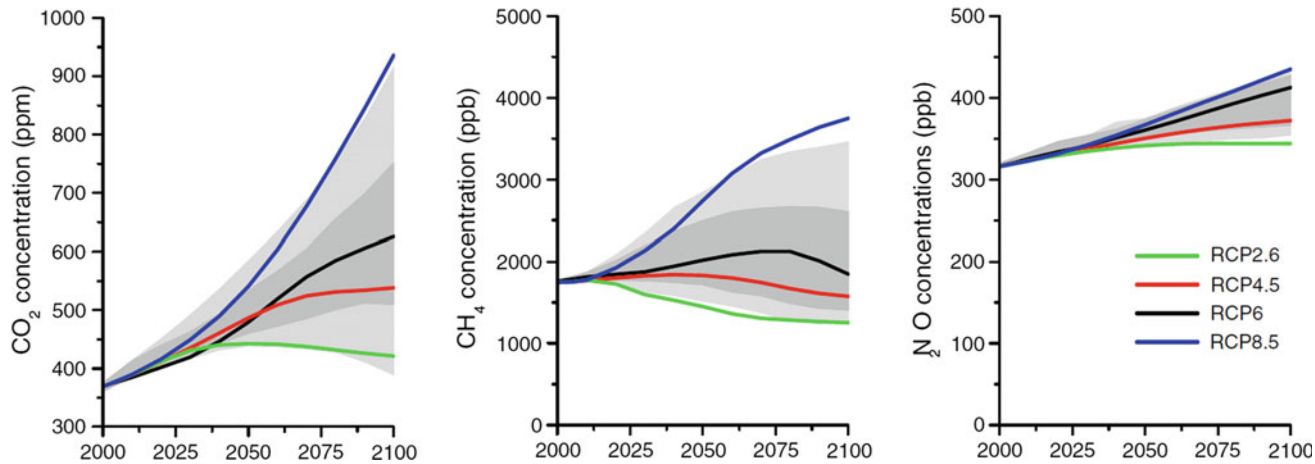
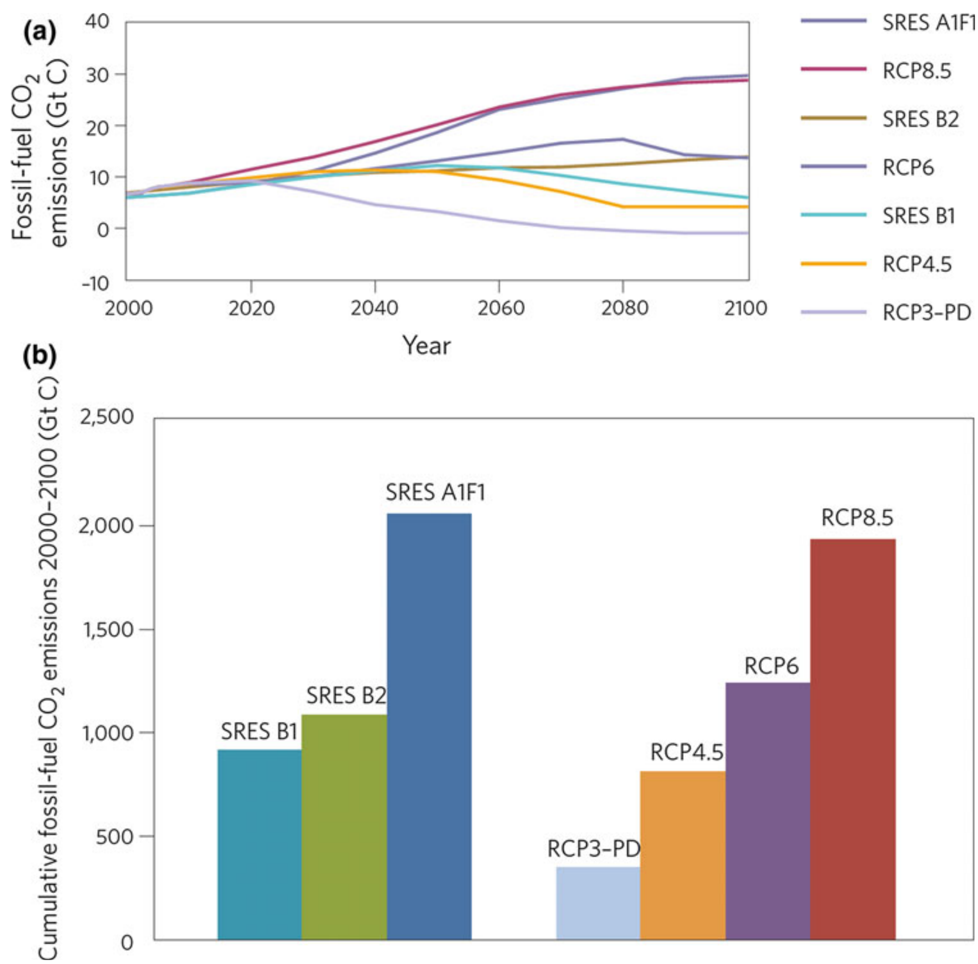


Fig. A4.4 Concentrations of the greenhouse gases carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) across the RCPs. The *grey area* indicates the 98th and 90th percentiles (*light/dark grey*) of an earlier emission study (EMF-22) (van Vuuren et al. 2011a)

Fuss et al. (2014) explored the need for negative emissions in more detail using a set of scenarios from IPCC Working Group III AR5 activities. They found that most emission pathways (101 of 116 RCP2.6 pathways) leading to concentrations of 430–480 ppm CO_2-equivalent (CO_2eq; CO_2 plus the other GHGs expressed as CO_2), consistent with limiting warming to below 2 °C, require global net negative emissions in the latter half of this century, as do many scenarios (235 of 653) that reach 480–720 ppm CO_2eq in 2100 (see also Fig. A3.1 in Annex 3).

Fig. A4.5 Fossil-fuel carbon dioxide (CO_2) emissions (**a**) and cumulative emissions over the period 2000–2100 (**b**) for the SRES scenarios A1FI, B2 and B1 and as estimated for the four representative RCPs (note RCP3-PD is also known as RCP2.6) (Raper 2012)



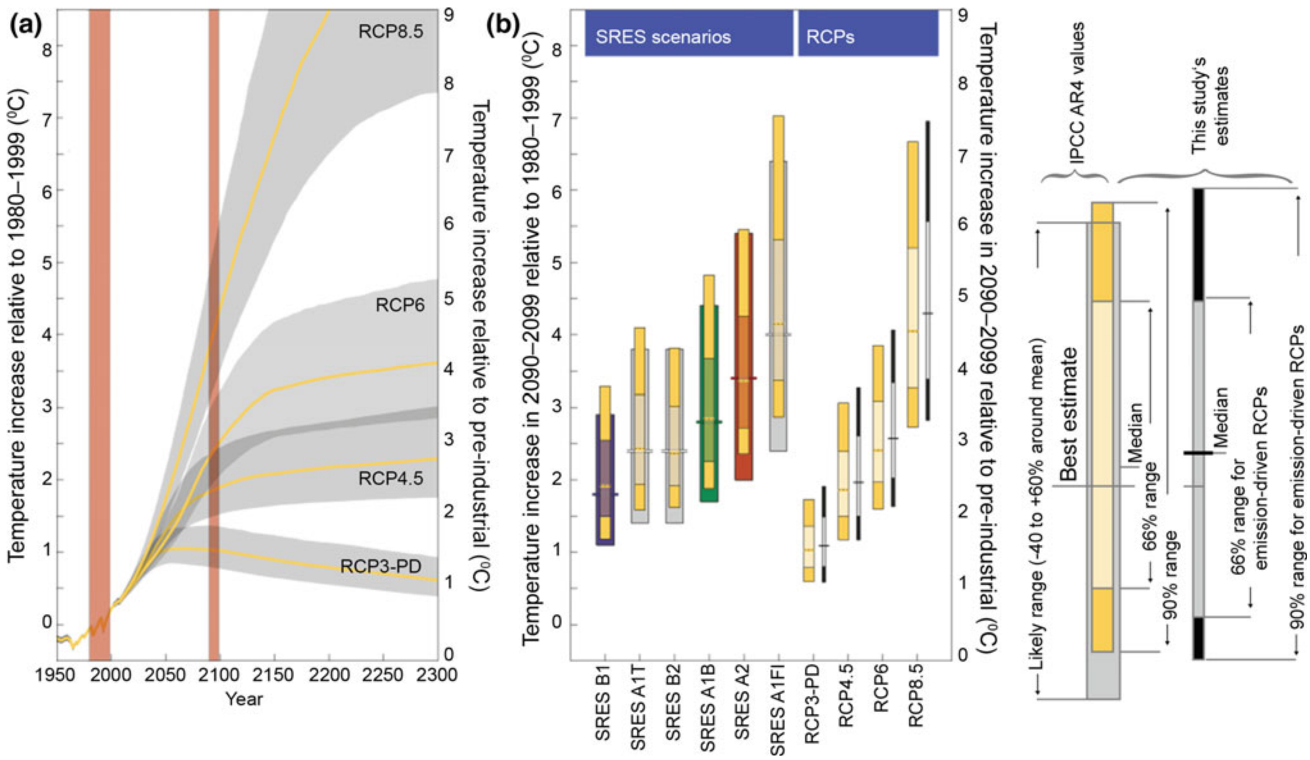


Fig. A4.6 Comparison of temperature projections for SRES scenarios and RCPs. **a** Time-evolving temperature distributions (66 % range) for the four concentration-driven RCPs computed with a representative equilibrium climate sensitivity (ECS) distribution and a model set-up representing closely the climate system uncertainty estimates of IPCC AR4 (*grey areas*). Median paths are shown in *yellow*. *Red shaded areas* indicate time periods referred to in '**b**'. **b** Ranges of estimated average temperature increase between 2090 and 2099 for SRES scenarios and RCPs respectively. Note that results are given both relative to 1980–1999 (*left scale*) and relative to the pre-industrial period (*right scale*). *Yellow* and *thin black ranges* indicate results of the reporting study; other ranges show AR4 estimates (see legend to the *right-hand side*). For RCPs, *yellow ranges* show concentration-driven results, whereas *black ranges* show emission-driven results (Rogelj et al. 2012)

A further key difference to earlier scenarios is that the RCPs are spatially explicit and provide information on a global grid at a resolution of approximately 60 km. This provides a good spatial and temporal distribution of emissions and land use changes. This is an important improvement because the actual location of some short-lived gases and particles has a strong influence on their regional warming potential. The RCPs also include a very wide range of land-use projections, addressing trends in cropland, grassland and other vegetated areas. The final RCP data sets comprise land use data, harmonised GHG emissions and concentrations, gridded reactive gas and aerosol emissions, and ozone and aerosol abundance fields. Global average surface temperature changes based on RCP-driven global projections are presented in Annex 3 (see Fig. A3.2).

A4.4 Relations Between SRES and RCP Scenarios

Reviews of climate change and related impact studies in several chapters of this book reveal that SRES-based as well as RCP-based projections are in use. The question "What is the relation between SRES and RCP scenarios?" is therefore relevant for researchers evaluating different studies to inform, for example, adaptation strategies. A first impression may be gained by comparing CO_2 emissions for the different scenarios (see Fig. A4.5). This indicates that some SRES and RCP scenarios follow a similar path and result in comparable cumulative emissions in 2100.

Rogelj et al. (2012) offered a more detailed comparison that was intended to bridge the gap between the old and new scenarios. They used a common model framework constrained by observations to ensure a low uncertainty link to changes in the past. Rogelj et al. (2012) gave probabilistic climate projections for all SRES and RCP marker scenarios and discussed the associated temperature projections (see also Raper 2012), for the latter see Fig. A4.6. According to this study three pairs of similar scenarios could be identified, they are compared for the 2100 time horizon in Table A4.4. Mapping old and new scenarios was also the focus of a study by van Vuuren and Carter (2014): In principle these authors concluded on the same matching scenario pairs as Rogelj et al. (2014).

A new high-resolution regional climate model (RCM) ensemble has been established for Europe including

Table A4.4 Similarities and differences between RCP and SRES scenarios based on temperature projections (all temperatures in this table are medians)

RCP	SRES with similar temperature increase in 2100	Main differences
RCP8.5	A1FI	Between 2035 and 2080, temperatures with RCP8.5 rise slower than with SRES A1FI, the reverse is true after 2080
RCP6.0	B2	Between 2060 and 2090, temperatures with RCP6.0 rise faster than with SRES B2 and slower during the other periods of the century
RCP4.5	B1	Until mid-century temperatures with RCP4.5 rise faster than with SRES B1, and then slower afterwards
RCP2.6	None	n.a.

The often-used SRES A1B scenario is not listed, because a similar RCP scenario for the 21st century does not exist (modified after Rogelj et al. 2012)

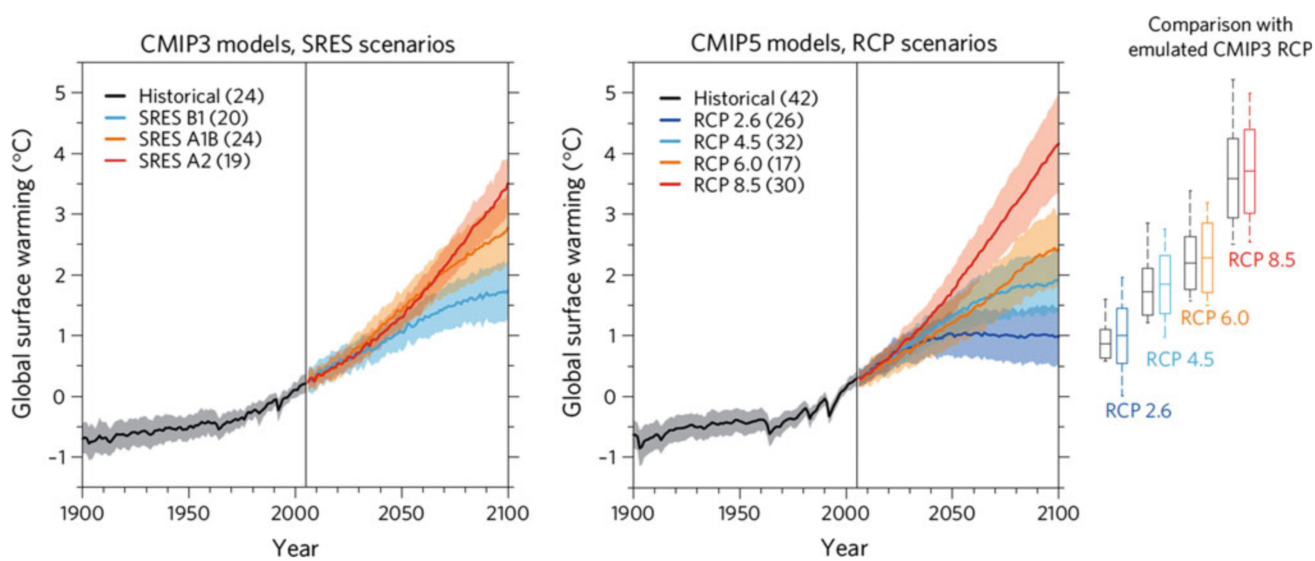


Fig. A4.7 Global surface temperature change (mean and one standard deviation as *shading*) relative to 1986–2005 for the SRES scenarios run by CMIP3 and the RCP scenarios run by CMIP5. The number of models is given in *brackets*. The box plots (mean, one standard deviation, and minimum to maximum range) are given for 2080–2099 for CMIP5 (*colours*) and for an energy balance model (MAGICC) calibrated to 19 CMIP3 models (*black*), both running the RCP scenarios (Knutti and Sedláček 2013)

the entire North Sea region within the World Climate Research Program Coordinated Regional Downscaling Experiment (EURO-CORDEX) initiative. The first set of simulations with a horizontal resolution of 12.5 km was completed for the RCP4.5 and RCP8.5 scenarios. These EURO-CORDEX ensemble results were compared to the SRES A1B results achieved within the ENSEMBLES project by Jacob et al (2014).

An additional point is that most of the SRES-based projections were generated using the older CMIP3 models, whereas the newer CMIP5 models were used for most RCP-based projections (for a review of the coupled model intercomparison projects—CMIP—see Annex 2). A full comparison of available climate change and impact studies needs to address this discrepancy. A study looking at this issue in more depth is that of Knutti and Sedláček (2013), in which emulated CMIP3 models were used for RCP-based projections. The major findings are summarised in Fig. A4.7. The different model generations result in differences in mean, standard deviation and range. The graphic suggests that the CMIP5 models show more warming for a given RCP than the emulated CMIP3 models, while the overall pattern of greater warming with higher forcing is robust.

A4.5 Concluding Remarks

Climate change projections are forced by emission scenarios. This annex describes the SRES and RCP scenarios in order to provide context for the projections discussed in the various chapters of this book. Both scenario sets offer a wide range of emission pathways, although only the RCP scenarios consider ambitious global warming abatement strategies. Of these, the RCP2.6 scenario is the most ambitious and the only one providing an emission pathway towards limiting with a high probability (around 66 %) global warming to below 2 °C above the pre-industrial global temperature.

For the North Sea region, available studies include those presenting results based on the older SRES scenarios as well as those presenting results based on the newer RCP scenarios. Many SRES and RCP scenarios can be paired, which is especially useful for the comparison and continuity of climate-impact studies. The three pairs—SRES A1F1/RCP8.5, SRES B2/RCP6 and SRES B1/RCP4.5—span the range of scenarios considered to date by most impact studies. The often-used SRES A1B scenario has no counterpart among the RCPs, and neither does the strong mitigation scenario RCP2.6 among the SRES scenarios.

In parallel to the construction of the RCPs, so-called shared socio-economic pathways (SSPs) have been developed with the help of integrated assessment models to reveal the driving forces behind the scenarios. An SSP database has been compiled by the research community, which is intended to enhance transparency of the process and to involve a large number of scientists in discussions around newly evolving scenarios (see IIASA 2015 for an update on the database). It is expected that many global and regional scenarios will emerge that are consistent with the new RCPs (Nakićenović et al. 2014).

Finally, it should be mentioned that RCM projections, employed to focus in higher grid resolution on limited areas such as the North Sea region, are linked to the scenarios via the driving GCMs, which provide their meteorological conditions (usually at the lateral boundaries) and sea surface temperatures.

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Annex 5: Facts and Maps

Ingeborg Nöhren

Facts concerning the Greater North Sea region are presented in Table A5.1. Figure A5.1 is a physiogeographical map, Fig. A5.2 shows different sea areas of the North Sea. Figure A5.3 gives an overview of existing and prospective uses and nature conservation areas of the North Sea region.

Table A5.1 Facts concerning the Greater North Sea region

Variable	
Length north-south[a]	960 km
Width east-west[a]	580 km
Surface area	750,000 km^2
Volume	94,000 km^3
Average depth[a]	95 m
Maximum depth	700 m (Norwegian Trench)
Annual river input	296–354 km^3
Drainage area	850,000 km^2
Population in drainage area (2000)	184 million
Sea surface temperature amplitude of the yearly cycle	2–7 °C (NW to SE)
Annual mean sea surface temperature	9.5 °C
Mean net inflow from the Atlantic in the north[b]	~2 million m^3 s^{-1} (2.32 Sv)
Mean net outflow to the Atlantic in the north[b, c]	~2 million m^3 s^{-1} (2.33 Sv)
Mean net inflow from the Baltic Sea[b]	15,000 m^3 s^{-1} (0.015 Sv)
Mean net inflow from Dover Strait[b]	160,000 m^3 s^{-1} (0.16 Sv)
Salinity	34–35 psu (central North Sea)
Difference between high and low water	0–8 m

All numbers taken from OSPAR (2000) unless otherwise indicated. OSPAR (2000) Quality Status Report (2000), Region II: Greater North Sea. OSPAR Commission, London

[a] http://www.mumm.ac.be/EN/NorthSea/facts.php

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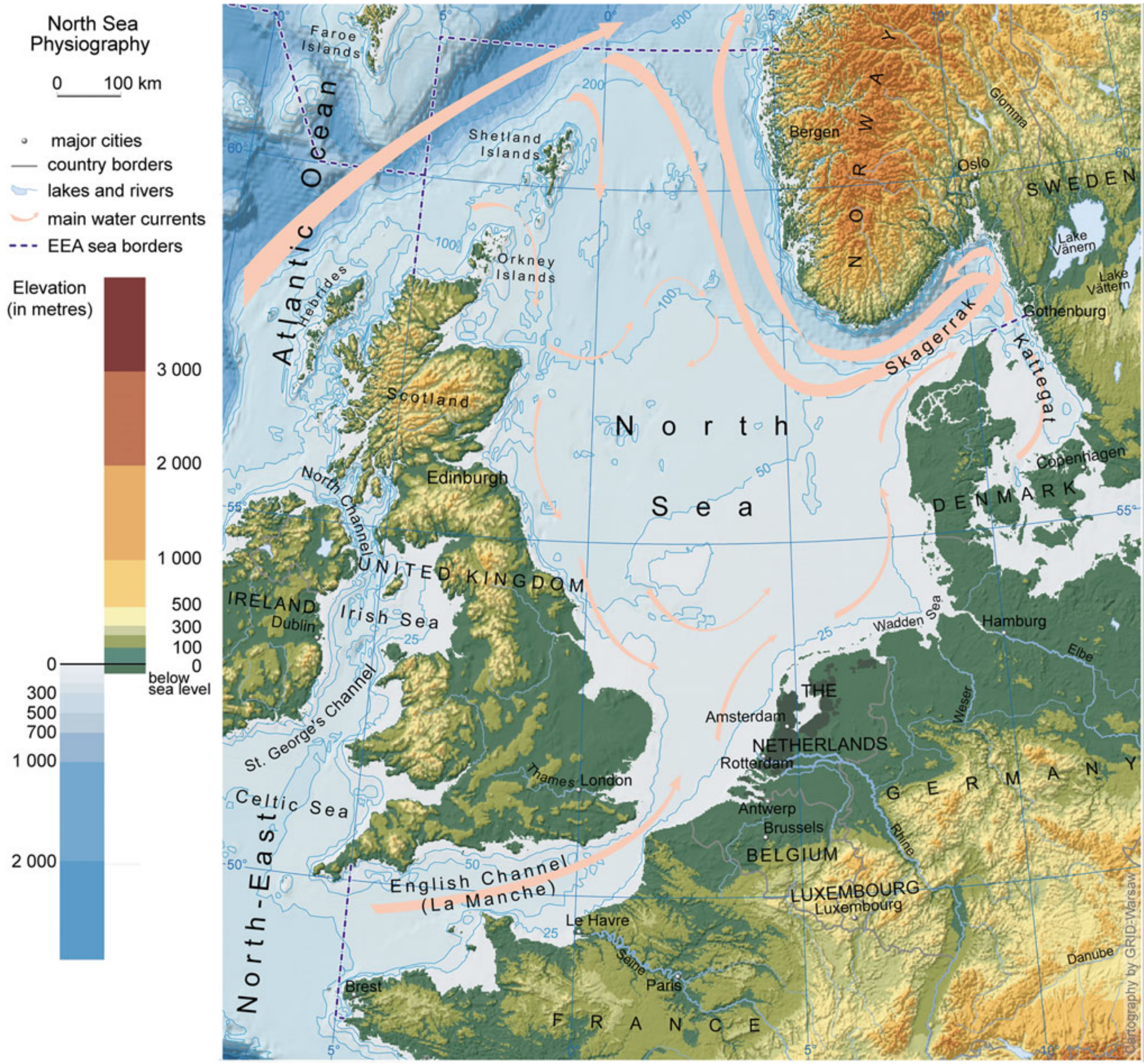

Fig. A5.1 Physiogeographical map of the Greater North Sea region (www.eea.europa.eu/data-and-maps/figures/north-sea-physiography-depth-distribution-and-main-currents)

Fig. A5.2 Different sea areas of the North Sea (Wikimedia Commons, licensed under Creative Commons Attribution-Share Alike 3.0 Unported)

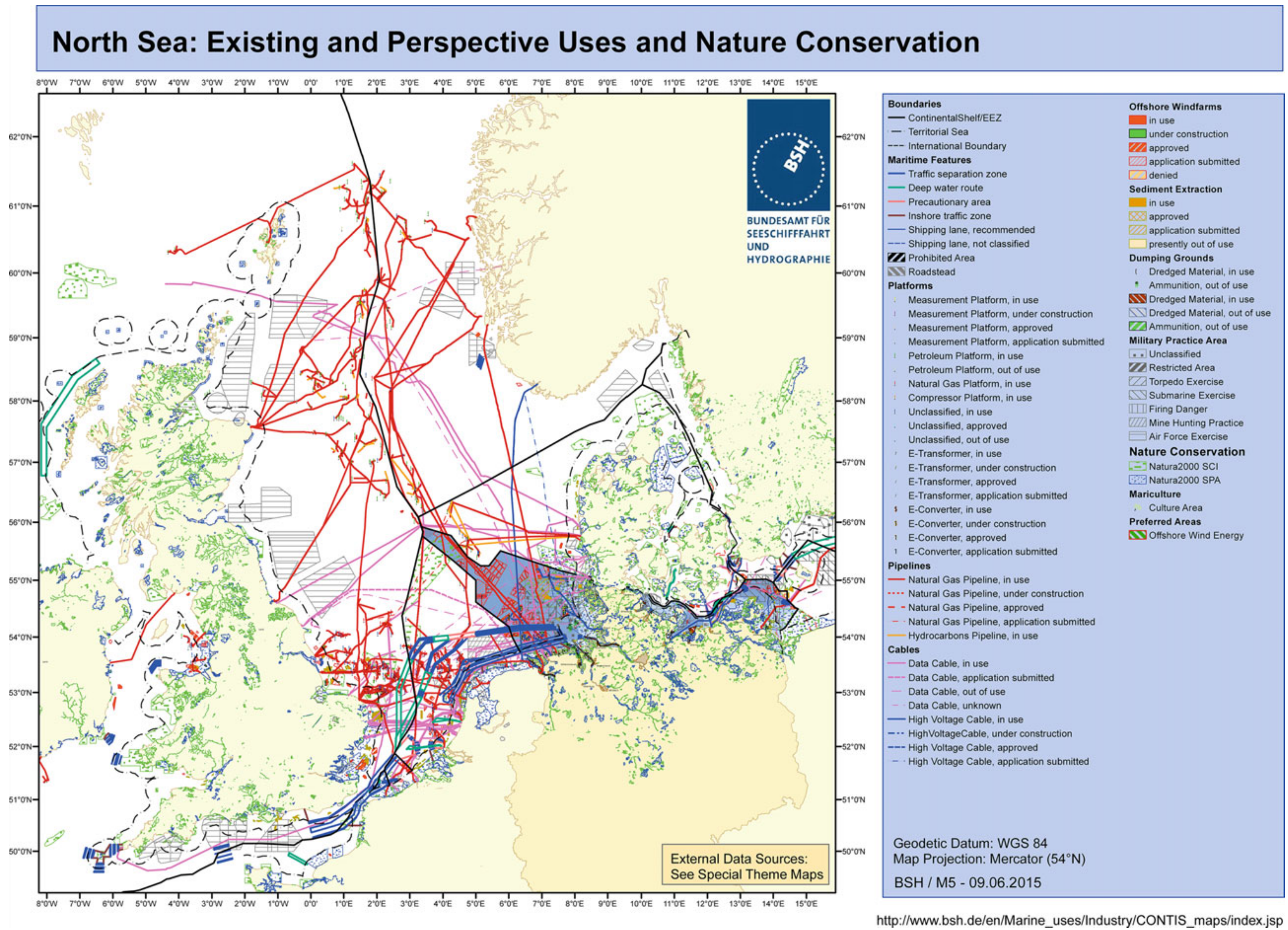

Fig. A5.3 Existing and prospective uses and nature conservation areas of the North Sea region (for higher resolution see: www.bsh.de/en/Marine_uses/Industry/CONTIS_maps/index.jsp, regularly updated)