Annex 4: Emission Scenarios for Climate Projections

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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

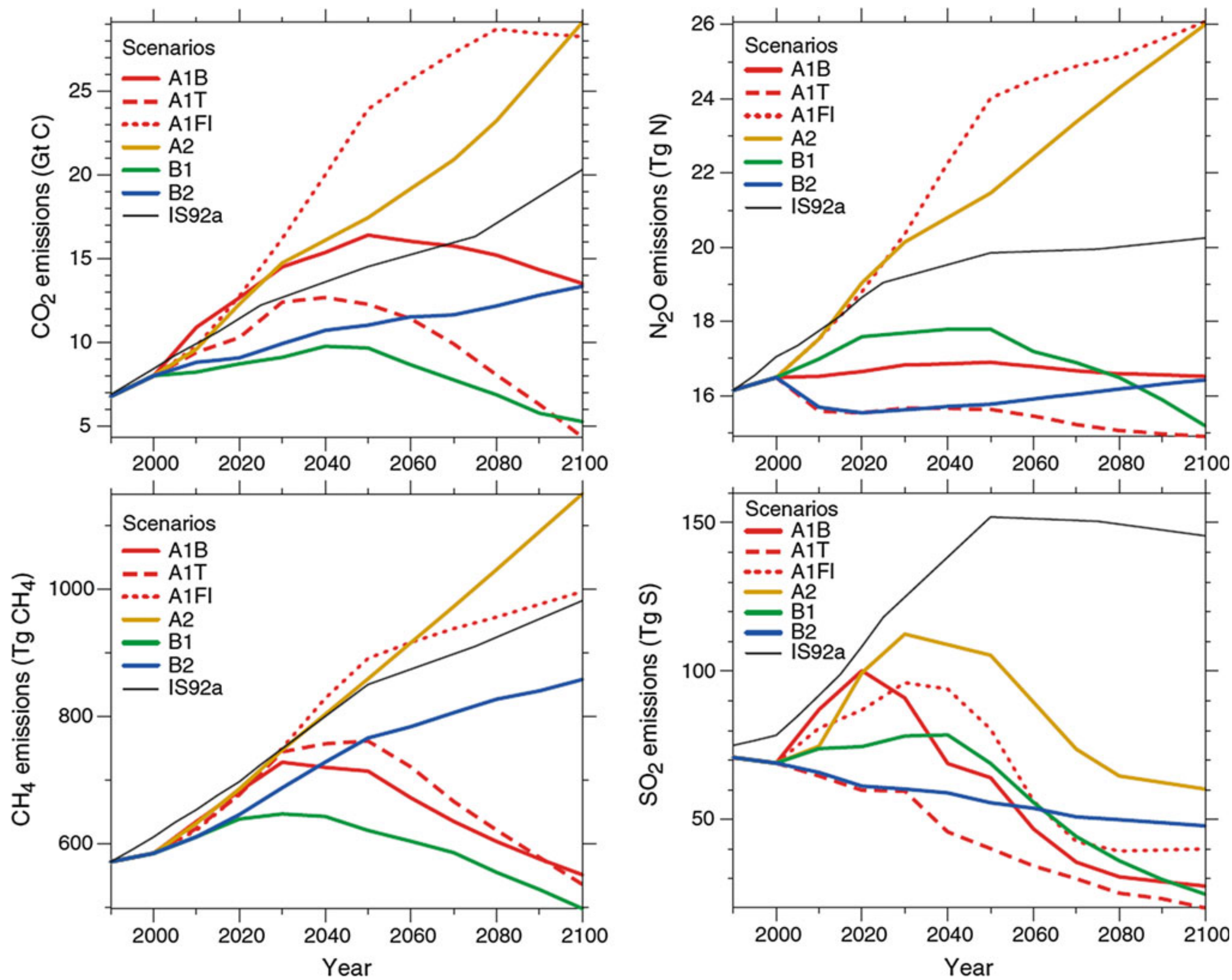

Fig. A4.1 Anthropogenic emissions of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and sulphur dioxide (SO_2) for the six illustrative SRES scenarios, A1B, A2, B1 and B2, A1FI and A1T. One of the scenarios used for projections made in the 1990s (IS92a) is also shown for comparison (IPCC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

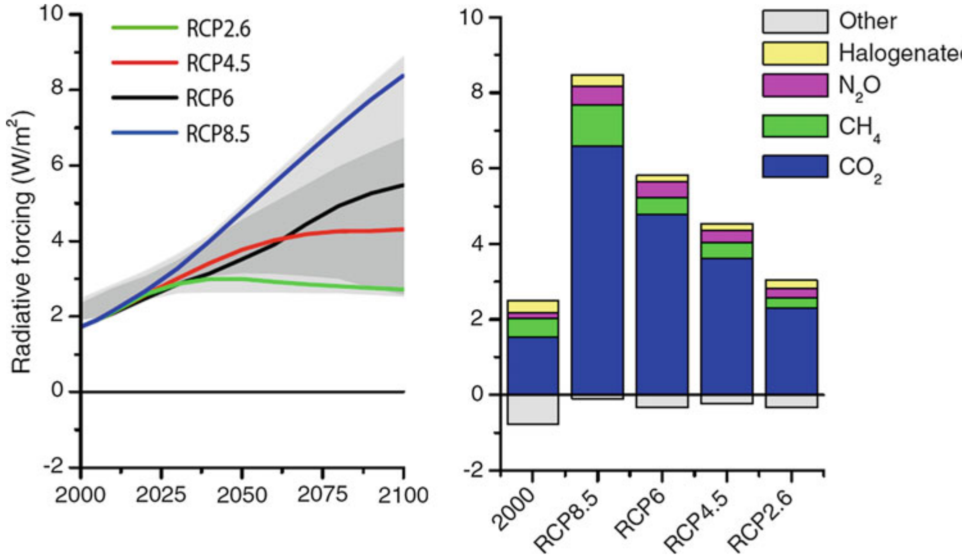

Fig. A4.2 Trends in radiative forcing (*left*) and 2100 forcing level per category (*right*). Forcing is relative to pre-industrial values and does not include land use (albedo), dust, or nitrate aerosol forcing (van Vuuren et al. 2011a)

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.

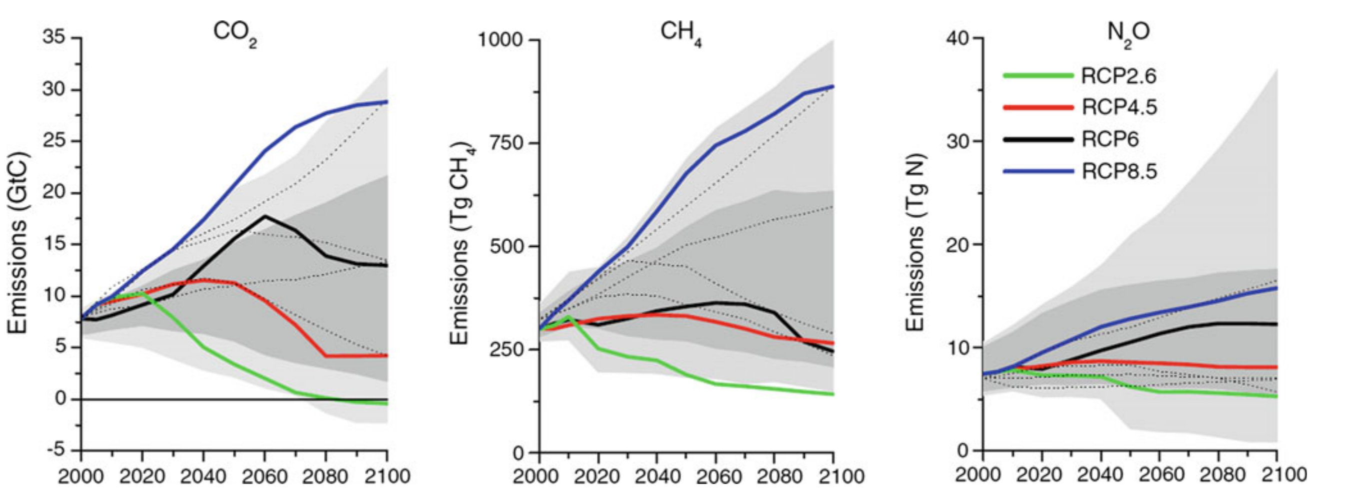

Fig. A4.3 Emissions of the main greenhouse gases carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) across the RCPs. The *grey area* indicates the 98th and 90th percentiles (*light/dark grey*) of the underlying scenarios from a literature survey. The *dotted lines* indicate four SRES marker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

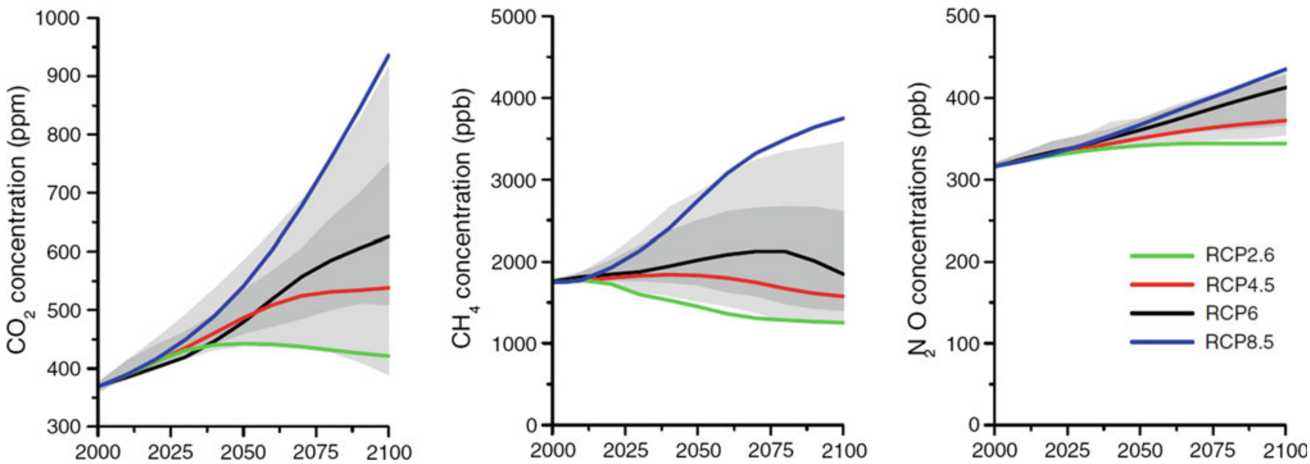

Fig. A4.4 Concentrations of the greenhouse gases carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) across the RCPs. The *grey area* indicates the 98th and 90th percentiles (*light/dark grey*) of an earlier emission study (EMF-22) (van Vuuren et al. 2011a)

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).

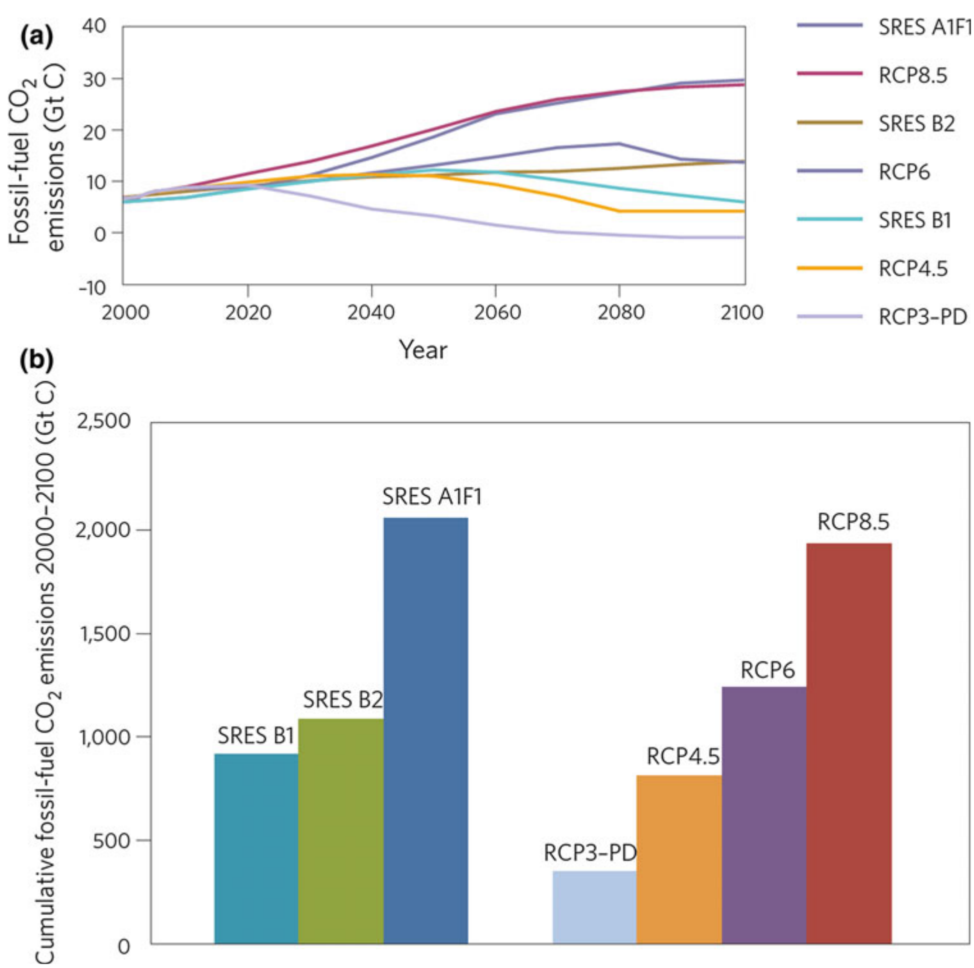

Fig. A4.5 Fossil-fuel carbon dioxide (CO_2) emissions (**a**) and cumulative emissions over the period 2000–2100 (**b**) for the SRES scenarios A1FI, B2 and B1 and as estimated for the four representative RCPs (note RCP3-PD is also known as RCP2.6) (Raper 2012)

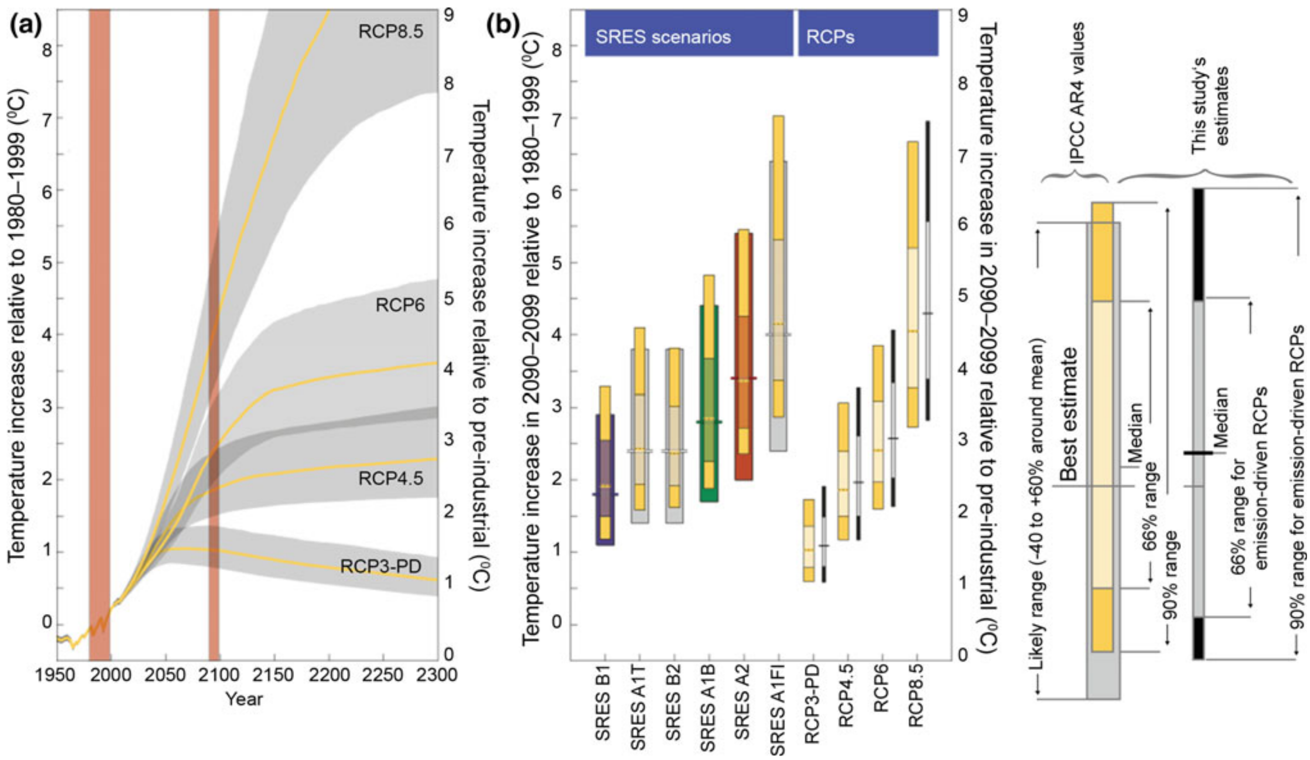

Fig. A4.6 Comparison of temperature projections for SRES scenarios and RCPs. **a** Time-evolving temperature distributions (66 % range) for the four concentration-driven RCPs computed with a representative equilibrium climate sensitivity (ECS) distribution and a model set-up representing closely the 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)

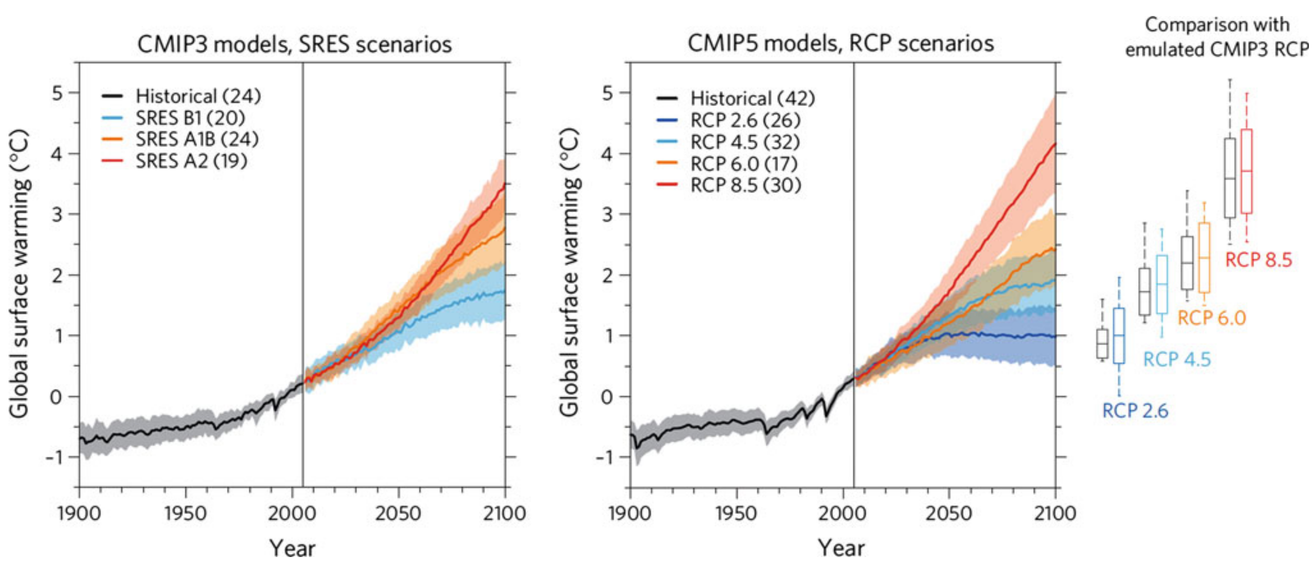

Fig. A4.7 Global surface temperature change (mean and one standard deviation as *shading*) relative to 1986–2005 for the SRES scenarios run by CMIP3 and the RCP scenarios run by CMIP5. The number of models is given in *brackets*. The box plots (mean, one standard deviation, and minimum to maximum range) 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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