Climate change scenarios – purpose and construction

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Abstract

In this article, the concept of scenarios is introduced and illustrated with the example of global and regional climate change scenarios.

Scenarios are descriptions of possible futures – of different plausible futures. Scenarios are not predictions but „storyboards“, a series of alternative visions of futures, which are possible, plausible, internally consistent but not necessarily probable (e.g., Schwartz, 1991; see also Tol, 2007b). The purpose of scenarios is to confront stakeholders and policymakers with possible future conditions so that they can analyze the availability and usefulness of options to confront the unknown future. Scenarios allow implementing measures now to avoid unwanted futures; they also may be used to increase chances for the emergence of favorable futures.

In daily life, we are operating frequently with scenarios. For instance, when planning in spring for a children’s birthday party next summer, we consider the scenarios of an outdoor party on a sunny day or an indoor party on a rainy day. Both scenarios are possible, plausible and internally consistent. Planning for a snowy day, on the other hand, is not considered, as this would be an inconsistent scenario.

In climate research, scenarios have been widely used since the introduction of the IPCC process in the end of the 1980s (Houghton et al., 1990, 1992, 1996, 2001). These scenarios are built in a series of steps. This series begins with *scenarios of* *emissions* of radiatively active substances, i.e., greenhouse gases, such as carbon dioxide or methane, and aerosols. These scenarios depend on a variety of developments unrelated to climate itself, in particular on population growth, efficiency of energy use, and technological development (Tol, 2007b). Many of these factors are unpredictable; therefore, a variety of sometimes ad-hoc assumptions are entering these scenarios.

In the next steps, the construction of scenarios is less ad-hoc, as they essentially process the emissions scenarios. The first step is to transform the emissions into atmospheric concentrations, which are then fed into global climate models[1]. Thus, from possible, plausible and internally consistent future emissions are derived estimates of possible, plausible and internally consistent future climate, i.e., seasonal means, ranges of variability, spectra, or spatial patterns. These are the *global climate change scenarios.* Effects of changes in the natural climate forcing factors such as changes

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*[1] There are different types of **climate models** (cf. McGuffie and Henderson-Sellers, 1997; Crowley and North, 1991; von Storch and Flöser, 2001, or Müller and von Storch, 2005). The simplest form are energy balance models, which describe in a rather schematic way the flux and fate of energy entering the atmosphere as solar radiation and leaving it as long- and short wave radiation. These models are meant as conceptual, minimum complexity tools, to describe the fundamental aspects o the thermodynamic engine "climate system". On the other end of complexity are the maximum complexity tools, which contain as many processes and details as is can be processed on a contemporary computer. Being limited by the computational resources, these models grow in complexity in time – simply because the computers become continuously more powerful. Such models are supposed to approximate the complexity of the real system. They simulate a sequence of hourly, or even more frequently sampled, weather, with very many atmospheric, oceanic and cryospheric variables – such as temperature, salinity, wind speed, cloud water content, upwelling, ice thickness etc. From these multiple time series, the required statistics (= climate) are derived. Thus, working with simulated data is similar to working with observed data. The only, and significant, difference is that one can perform experiments with climate models, which is impossible with the real world. However, present days climate models are coarse and the modelling of several processes related to the water and energy cycles are not well understood and only crudely described in these models.*

in sun radiation, or volcano eruptions are often not considered in these scenarios. Instead the scenarios try to vision what will happen in the future depending on anthropogenic changes (even if changes of land-use are usually not considered). We may thus call them *anthropogenic climate change scenarios*.

The global climate models are supposed to describe climate dynamics on spatial scales[2] of, say, 1000 km and more. They do not resolve the geographical features such as the details of the Baltic Sea catchment. For instance, in the global models, the Baltic Sea is not connected to the North Sea through narrow sills; instead, the Baltic Sea is something like an extension of the North Sea with a broad link. In addition, the Scandinavian mountain range is shallow (Figure 1). Therefore, in a second step, possible future changes of regional scale climatic features are derived using regional climate models[3]. These models are based on the concept of "downscaling",

[2] *„**Scales**" is a fundamental concept in climate science. The term refers to typically lengths or typical durations of phenomena or processes. Obviously, this definition is fuzzy. Scales necessarily refer only to orders of magnitude. Global scales refer to several thousand kilometres and more; the continental scale to a few thousand kilometres and more, and regional scales to hundred kilometres and more. For instance, the Baltic Sea is a regional feature of the global climate system.*

When constructing climate models the equations can only be resolved within a limited resolution. Dynamic features larger than the grid domain need to be prescribed, while features below the grid size needs to be parameterized. Typical atmospheric and oceanic processes that need to be parameterized in climate models are indicated in Figure 2.

[3] ***Regional climate models** are built in the same way as global climate models – with the only and significant difference that they are set up on a limited domain with time-variable lateral boundary conditions. Mathematically this is not a well-posed problem, i.e., there is not always one and only one solution satisfying both the ruling differential equations and the boundary constraints. By including a lateral "sponge-zone" along the lateral boundaries, within which the internal solution and the externally given boundary conditions are nudged, it is practically ensured that there is a solution, and that instabilities are avoided. Most present day regional climate models only*

according to which smaller scale weather statistics (regional climate) are the result of a dynamical interplay of larger-scale weather (continental and global climate) and regional physiographic detail (von Storch, 1995, 1999). There are two approaches for downscaling (see, e.g., Giorgi et al., 2001) – namely empirical or statistical downscaling, which employs statistically fitted links between variables representative for the large large-scale weather state or weather statistics, and locally or regionally significant variables. The alternative is dynamical downscaling, which employs a regional climate model. Such regional models are constrained by the large-scale state simulated by the global models along the lateral boundaries and sometimes in the interior. With horizontal grid sizes of typically 10 to 50 km, such models resolve features with minimum scales of some tens to a few hundred of kilometers. They also simulate the emergence of rare events, such as strong rainfall episodes and strong windstorms.

Methodologically, the *anthropogenic* climate change scenarios are *conditional predictions*. After the emissions scenarios are given, no further ad-hoc decisions are required. Significant assumptions are required only for the design of the emission scenarios. These assumptions refer to socio-economic processes, which lead to emissions. Each set of socio-economic assumptions is associated with another climate development. However, they all share a number of changes, namely an increase of air and sea surface temperature and a rise of water levels. Thus, the conditional predictions agree independently of the specific conditioning assumptions on a

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downscale the global models and they thus do not send the information back to the global scale. This implies that they are strongly controlled by the global climate model.

The advantage of regional climate models is that they provided an increased horizontal resolution. Therefore, they can simulate regional detail as is needed for many impact studies.

general increase of temperature and sea level – and these conditional predictions become *unconditional predictions* with respect to these properties.

When dealing with regional or local scenarios, one has to keep in mind that not only global and regional climate changes, but that the effect of climate on regional and local economic and ecological conditions depends on many other factors, which may also change. For instance, changing land-use may locally be of comparable significance as the influence of climate changes. Thus, a complete analysis on the regional level needs an additional set of scenarios which describes the changing usage of the local and regional environment (e.g., Grossmann, 2005, 2006; Bray et al., 2003).

1 Emission scenarios

A number of emission scenarios has been published as „IPCC Special Report on Emissions Scenarios" (SRES; http://www.grida.no/climate/ipcc/emission) prepared by economists and other social scientists for the Third Assessment report of the IPCC (see also Tol, 2007b). They utilize scenarios of greenhouse gas and aerosol emissions, or of changing land use.

(A1) a world of rapid economic growth and rapid introduction of new and more efficient technology,

(A2) a very heterogeneous world with an emphasis on family values and local traditions,

(B1) a world of ``dematerialization'' and introduction of clean technologies,

(B2) a world with an emphasis on local solutions to economic and environmental sustainability.

The scenarios do not anticipate any specific mitigation policies for avoiding climate change. The authors emphasize "no explicit judgments have been made by the SRES team as to their desirability or probability".

The **Scenarios A2 and B2** were widely used in recent years. Therefore, we explain the socio-economic background of these scenarios in more detail (for a summary for the other two scenarios, refer to Müller and von Storch, 2004):

SRES describes the A2-scenario as follows: “... characterized by lower trade flows, relatively slow capital stock turnover, and slower technological change. The world ``consolidates'' into a series of economic regions. Self-reliance in terms of resources and less emphasis on economic, social, and cultural interactions between regions are characteristic for this future. Economic growth is uneven and the income gap between now-industrialized and developing parts of the world does not narrow. People, ideas, and capital are less mobile so that technology diffuses more slowly. International disparities in productivity, and hence income per capita, are largely maintained or increased in absolute terms. With the emphasis on family and community life, fertility rates decline relatively slowly, which makes the population the largest among the storylines (15 billion by 2100). Technological change is more heterogeneous. Regions with abundant energy and mineral resources evolve more resource-intensive economies, while those poor in resources place a very high priority on minimizing import dependence through technological innovation to improve resource efficiency and make use of substitute inputs. Energy use per unit of GDP declines with a pace of 0.5 to 0.7% per year. Social and political structures diversify; some regions move toward stronger welfare systems and reduced income inequality, while others move toward ``leaner'' government and more heterogeneous income distributions. With substantial food requirements, agricultural productivity is one of the main focus areas for innovation and research, development efforts, and environmental concerns. Global environmental concerns are relatively weak.''

In B2, there is “... increased concern for environmental and social sustainability. Increasingly, government policies and business strategies at the national and local levels are influenced by environmentally aware citizens, with a trend toward local self-reliance and stronger communities. Human welfare, equality, and environmental protection all have high priority, and they are addressed through community-based social solutions in addition to technical solutions. Education and welfare programs are pursued widely, which reduces mortality and fertility. The population reaches about 10 billion people by 2100. Income per capita grows at an intermediate rate. The high educational levels promote both development and environmental protection. Environmental protection is one of the few truly international common priorities. However, strategies to address global environmental challenges are not of a central priority and are thus less successful compared to local and regional environmental response strategies. The governments have difficulty designing and implementing agreements that combine global environmental protection. Land-use management becomes better integrated at the local level. Urban and transport infrastructure is a particular focus of community innovation, and contributes to a low level of car dependence and less urban sprawl. An emphasis on food self-reliance contributes to a shift in dietary patterns toward local products, with relatively low meat consumption in countries with high population densities. Energy systems differ from region to region. The need to use energy and other resources more efficiently spurs the development of less carbon-intensive technology in some regions. Although globally the energy system remains predominantly hydrocarbon-based, a gradual transition occurs away from the current share of fossil resources in world energy supply."

Expected emissions of greenhouse gases and aerosols into the atmosphere are derived from these assumptions and descriptions. Figure 3 shows the expected SRES scenarios for carbon dioxide (a representative of greenhouse gases; in gigatons per year) and sulfate dioxide (a representative of anthropogenic aerosols; in megatons sulfur).

The SRES scenarios are not unanimously accepted by the economic community. Some researchers find the scenarios internally inconsistent (Tol, 2007b). A documentation of the various points raised, is provided by the Select Committee of Economic Affairs des House of Lords in London (2005). A key critique is that the expectation of economic growth in different parts of the world is based on market exchange ranges (MER) and not on purchasing power parity (PPP). Another aspect is the implicit assumption in the SRES scenarios that the difference in income between developing and developed countries will significantly shrink until the end of this century (Tol, 2007a)[4]. These assumptions, the argument is, lead to an exaggeration of expected future emissions.

2 Scenarios of *anthropogenic* global climate change

The emission scenarios are first transformed into scenarios of atmospheric loadings of greenhouse gases and aerosols. Then, the global climate models derive from these concentrations – without any other externally set specifications – sequences of hourly weather for typically hundred years. A large number of relevant variables are calculated, for the troposphere, the lower stratosphere and the oceans, but also at the different boundaries of land, air, ocean and sea ice – such as air temperature, soil temperature, sea surface temperature, precipitation, salinity, sea ice coverage or wind speed.

Global climate models suffer to some degree from systematic error, so-called biases. Globally, these errors are not large, but they can be regionally large and are too large to determine the expected climate changes only from a simulation with, for instance, elevated greenhouse gas concentrations. Instead, the climate change is determined by comparing the statistics of a “scenario simulation” with anthropogenic greenhouse and aerosol levels with the statistics of a “control run”, which is supposed to represent contemporary conditions with unchanged atmospheric composition. The difference between the control run and present climate conditions provide us with a

[4] *Add a reference if this is dealt with in Tol’s contribution to this book.*

measure of the quality of the climate simulation. If this difference is large compared to the scenario change, the climate simulation should be interpret with care.

Figure 4 shows as an example the expected change of winter air temperature for the last 30 years of the 21st century in the scenario A2 and in the scenario B2. This change is given as the difference of 30 years mean in the scenario run and in the control run. The air temperature rises almost everywhere; the increase is larger in the higher-concentration scenario A2 than in the lower-concentration B2. Temperatures over land rise faster than over the oceans, which are thermally more inert than air temperatures over land. In Arctic regions, the increase is particularly strong – this is related to the partial meting of permafrost and sea ice.

3 Regional *anthropogenic* climate change

A number of projects, as e.g. PRUDENCE (Christensen et al., 2002), have used regional climate models to derive regional climate change scenarios for Central and Northern Europe. A major result was that the regional models return rather similar scenarios when they are forced by the same global climate change scenario (e.g., Woth et al., 2005; Déqué et al., 2005)– so that the choice of the regional climate model is of minor relevance. However, if different driving global climate change scenarios are used – by using different emission scenarios or different global climate models – the differences become larger (e.g., Woth, 2005, Déqué et al., 2005). If higher levels of anthropogenic forcing are applied, then on average the regional changes become stronger, even if not necessarily in a statistically significant manner. This lack of significance is related to the fact that the signal-to-noise ratio of systematic change and weather noise gets smaller if the considered spatial scales are reduced.

A joint feature of all regional simulations is that it is getting warmer; frequency distributions tend to become broader with respect to central European summer rainfall (Christensen and Christensen, 2003) and North Sea winter wind speeds (Woth, 2005).

As an example, the expected changes of winter (DJF – December/January/February) mean temperatures are shown in Figure 5 – The different model configurations (two global models, two regional models) indicate that when the snow cover retreats to the north and to the east, the climate in the Baltic Sea catchment undergoes large changes. A common feature in all regional downscaling experiments is the stronger increase in wintertime temperatures compared to summertime temperatures in the northern and eastern part of the Baltic Sea catchment (e.g. Christensen et al., 2003; Déqué et al., 2007).

4 Literature

Bray, D., Hagner, C. and I. Grossmann, 2003: Grey, Green, Big Blue: three regional development scenarios addressing the future of Schleswig Holstein. GKSS-Report 2003/25, GKSS Research Center, Geesthacht 2003.

Christensen, J.H. and O.B. Christensen, 2003: Severe summertime flooding in Europe. Nature, Vol. 421, p. 805-806

Christensen, J.H., T. Carter, and F. Giorgi, 2002: PRUDENCE employs new methods to assess European climate change, EOS, Vol. 83, p. 147.

Crowley, T.J. and G. R. North, 1991: *Paleoclimatology.* Oxford University Press, New York, 330 pp.

Déqué, M., R. G. Jones, M. Wild, F. Giorgi, J. H. Christensen, D. C. Hassell, P.L. Vidale, B. Rockel, D. Jacob, Erik Kjellström, M. de Castro, F. Kucharski and B. van den Hurk, 2007: Global high resolution versus Limited Area Model climate change projections over Europe: quantifying confidence level from PRUDENCE results. Clim Dyn (in press)

Giorgi, F., B. Hewitson, J. Christensen, M. Hulme, H. von Storch, P. Whetton, R. Jones, L. Mearns and C. Fu, 2001: Regional climate information - evaluation and projections. In J.T. Houghton et al (eds.): *Climate Change 2001. The Scientific Basis*, Cambridge University Press, 583-638

Grossmann, I., 2005: Future Perspectives for the Lower Elbe Region 2000-2030: Climate Trends and Globalisation. PhD Thesis, Hamburg University

Grossmann, I., 2006: Three scenarios of the greater Hamburg region. Futures 38 (1), pp. 31-49.

Houghton, J.T., B.A. Callander and S.K. Varney (eds), 1992: *Climate Change 1992*. Cambridge University Press, 200 pp.

Houghton, J.T., Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell and C.A. Johnson, 2001: *Climate Change 2001: The Scientific Basis*. Cambridge University Press, 881 pp.

Houghton, J.L., G.J.Jenkins and J.J. Ephraums (eds), 1990: *Climate Change. The IPCC scientific assessment*. Cambridge University Press, 365 pp.

Houghton, J.T., L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg and K. Maskell (eds), 1996: *Climate Change 1995. The Science of Climate Change*. Cambridge University Press ISBN 0 521 56436-0, 572 pp.

House of Lords, Select Committee on Economic Affairs, 2005: *The Economics of Climate Change.* Volume I: Report, 2nd Report of Session 2005-06, Authority of the

House of Lords, London, UK; The Stationery Office Limited, HL Paper 12-I (http://www.publications.parliament.uk/pa/ld/ldeconaf.htm#evid)

McGuffie, K., and A. Henderson-Sellers, 1997: A climate modelling primer. 2nd edition, John Wiley & Sons, Chichester, Great Britain, 253 pp, ISBN 0-471-95558-2

Müller, P., and H., von Storch, 2004: Computer Modelling in Atmospheric and Oceanic Sciences: Building Knowledge. Springer Verlag Berlin - Heidelberg - New York, 304pp, ISN 1437-028X

Schwartz, P., 1991: *The art of the long view*. John Wiley & Sons, 272 pp

Tol, R.S.J., 2007a: Exchange rates and climate change: An application of FUND. Climatic Change (in press)

Tol. R.S.J., 2007b: Economic scenarios for global change, this volume

von Storch, H., 1995: Inconsistencies at the interface of climate impact studies and global climate research. - Meteorol. Zeitschrift 4 NF, 72-80

von Storch, H., 1999: The global and regional climate system. In: H. von Storch and G. Flöser: *Anthropogenic Climate Change*, Springer Verlag, ISBN 3-540-65033-4, 3-36

von Storch, H., and G. Flöser (Eds.), 2001 *Models in Environmental Research*. Proceedings of the Second GKSS School on Environmental Research, Springer Verlag ISBN 3-540-67862, 254 pp.

Woth, K., R. Weisse and H. von Storch, 2005: Dynamical modelling of North Sea storm surge extremes under climate change conditions - an ensemble study. Ocean Dyn. DOI 10.1007/s10236-005-0024-3

Woth, K., 2005: Projections of North Sea storm surge extremes in a warmer climate: How important are the RCM driving GCM and the chosen scenario? Geophys. Res. Letters32, L22708, doi: 10.1029/2005GL023762

Figure 1 Typical different atmospheric model grid resolutions with corresponding land masks. Left: T42 used in global models, right: 50 km grid used in regional models (courtesy: Ole Bøssing-Christensen)

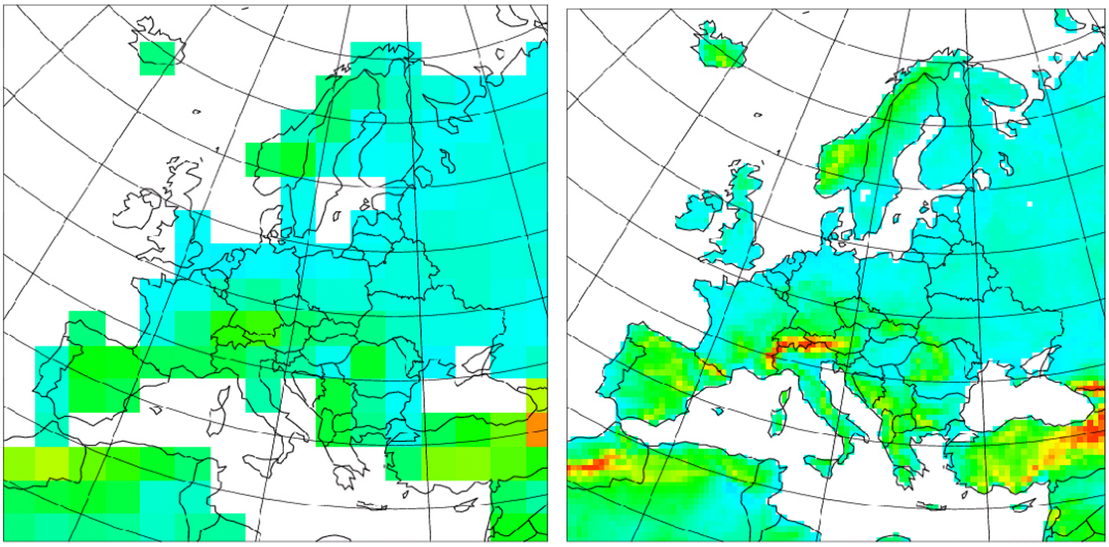
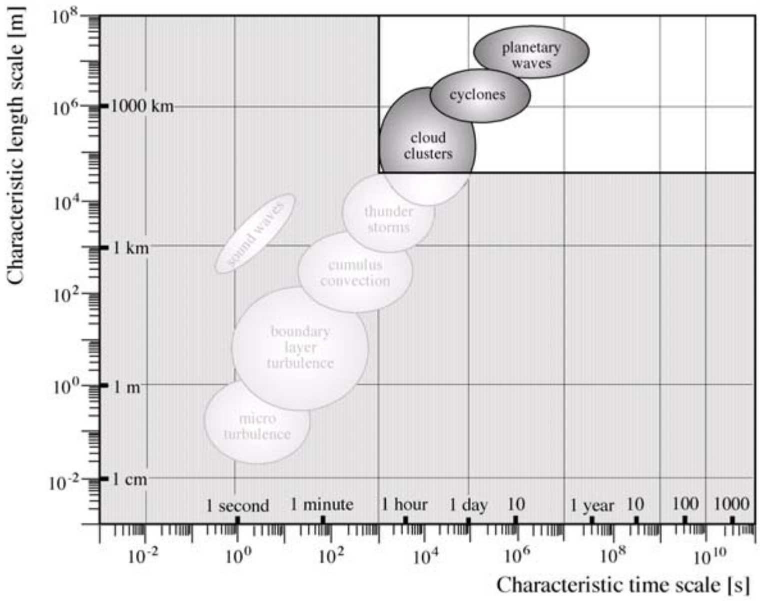


Figure 2 Spatial and temporal scales of some major processes in the atmosphere (a) and in the ocean (b). In the figures the grey area represents sub-grid scales in common global models, while the visible parts in the upper right corners represent the processes which climate models often aim to resolve (Redrawn from Müller and Storch, 2004).

(a)



(b)

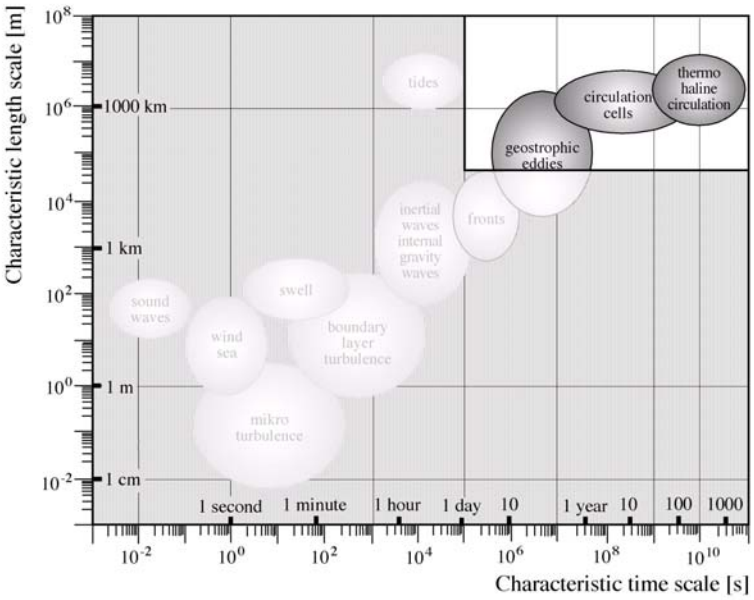


Figure 3. Scenarios of possible, plausible, internally consistent but not necessarily probable future emissions of carbon dioxide (a representative of greenhouse gases; in gigatons C) and of sulphate dioxide (a representative of anthropogenic aerosols; in megatons S). A1, B1, A2 and B2 are provided by SRES, IS92a is a scenario used in the Second Assessment Report of the IPCC in 1995.

Figure 4 Global scenarios of the air temperature change (in K) at the end of the 21st century, as determined with a global climate model forced with A2 and B2 emissions. Courtesy: Danmarks Meteorologiske Institut.

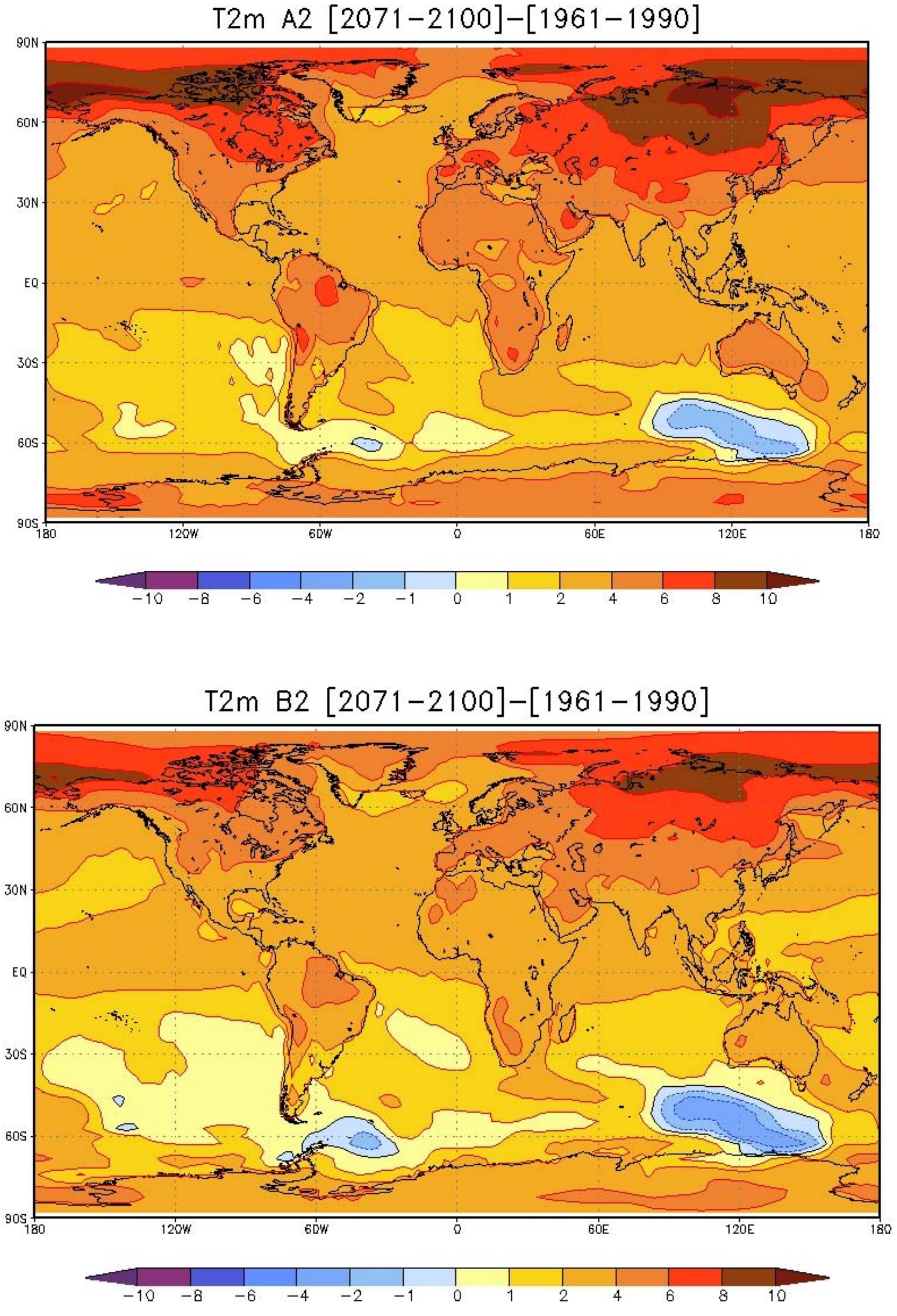


Figure 5. Temperature change (in K) for winter (DJF) between the periods 1961-1990 and 2071-2100 according to the SRES A2 scenario. Plots on the left used HadAM3H as boundary conditions, plots on the right used ECHAM4/OPYC3 as boundaries. For each season the upper row is the DMI regional model HIRHAM, the lower row is the SMHI model RCAO. Note that the ECHAM4/OPYC3 scenario simulations used as boundaries are different for the two downscaling experiments. The Baltic Sea catchment is indicated by the thick pale contour.