Anthropogenic Climate Change

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Scientific understanding of anthropogenic global climate change has advanced notably in recent years, and led to commensurate developments of mitigation strategies. International discussions on mitigation are primarily founded on our present understanding of global-scale change. Opposed to mitigation, adaptation is inherently a local and regional scale issue, and limited by the measure of confidence in the projected changes at these scales. It is at regional scales that credible information of probable climate change and the associated uncertainties is mostly needed. The possible consequences of climate change within some regions may even motivate some countries to commit to and argue for further mitigation practises.

Ideally Global Climate Models (GCMs) should be able to provide information at the regional scale they are able to resolve, but the majority of efforts in model development have been concentrated on improving the ability to describe specific geophysical phenomenons, e.g., El Niño, monsoon systems, sea-ice, etc. thereby at the same time obviously lacking specific attention to certain aspects of model performance in many other regions of the World. Therefore, alternative methods have been developed to derive detailed regional information in response to geophysical processes at finer scales than that resolved by GCMs. Through nested Regional Climate Models (RCMs) or empirical downscaling, these developments in turn have generated new and alternative ways to assess important regional processes central to climate change. This further allows development and validation of models to simulate the key dynamical and physical processes of the climate system.

Within the impacts and adaptation community there is a growing move toward integrated assessment, wherein regional climate change projections form a principal factor for decision support systems aimed at reducing vulnerability (Bales et al., 2004). At present the regional projections are perhaps the weakest link in this process, and the bulk of information readily available for policy and resource managers (such as via the IPCC DDC) is largely derivatives of GCMs, the data of which have limited skill in accurately simulating local scale climates, especially as regards the key parameter of precipitation. GCM data are commonly mapped as continuous fields (as in IPCC, 2001), which do not convey the low skill of the model for many regions, or are area aggregated (as in IPCC 2001) which renders the results of little value for local application.

In view of the pressing need for regional projections, much effort has been expended in recent years on developing regional projections through the above mentioned methodologies, and significant advances made to downscale the GCM skilful scale to the regional and local scales, either through high resolution dynamical modelling, or via empirical cross scale functions. However, to date, much of the work remains at the level of methodological development. Climate change projections that are tailored to the needs of the impacts community, and which demonstrate convergence of the projections across different forcing GCMs, are only now beginning to become more available. An additional challenge is to be able to anchor the regional climate projections reasonably well within a given set of emission scenarios, otherwise the notion that climate sensitivity might be more uncertain than previously believed would indicate that regional results would not be important at all, given the large-scale uncertainties.

It is evident that the climate of a given region is determined by the interaction between external forcings and atmospheric and oceanic circulations that occur at many spatial scales, for a wide range of temporal scales. Examples of regional and local scale forcings are those due to complex topography, land-use characteristics, inland bodies of water, land ocean contrasts, atmospheric aerosols, radiatively active gases, snow, sea ice, and ocean current distribution. Moreover, teleconnection patterns such as ENSO and NAO can strongly influence the climate variability of a region. The difficulties related to the simulation of regional climate and climate change are therefore quite apparent. Many of these difficulties have troubled a quantitative assessment of projected regional climate changes for both the regional mean state and particularly regarding extreme events and forced scientists to put relatively low confidence in many of the specific regional projection statements. Some of the key priorities to address this problem and progress made are:

GCMs

GCMs have steadily improved their general performance although not necessarily in all regions for all variables analysed, many of the state-of-the-art GCMs has been run for a great range of forcing scenarios and much more attention to both the general performance and aspects of climate change response of these models at the regional scale has taken place in recent uears. Likewise a considerable effort has gone into the analysis of these model simulations in the evaluation of simulated climate variability and extreme events. The 20-model ensemble of global models assembled in the PCMDI/AR4 archive has provided the clearest view to date of which aspects of continental and sub-continental climate changes are robust across models and which are not. Perturbed physics model ensembles (e.g., Murphy et al., 2004) are beginning to add to this information as well. There are a series of high resolution time-slice studies with uncoupled atmospheric models, ranging up to the 20 km resolution (e.g., Mizuta et al., 2005).

RCMs

While most of the RCM work on climate change issues dealt with until recently only considered simulations of limited duration (months to a decade), with hardly any study exploring time scale beyond a decade (e.g. IPCC, 2001, Appendix 10.3), experiments with RCMs of 20–30 year duration have become standard by many groups around the world (e.g., Christensen et al., 2002, 2006; Leung et al., 2004). This has enabled a more stringent validation of their performance in climate mode, and the general quality and understanding of RCM performance for many regions have greatly improved. The need for comparative studies using different RCMs to downscale climate change information from GCMs has also been confirmed by the scientific community. Christensen et al. (2001) with later updates by Rummukainen et al. (2003), for example combined the information from four different RCM climate change experiments for Scandinavia. They showed that by adding information from different runs and applying a simple pattern scaling argument, it became possible to quantify the uncertainty related to projections in the mean climate state, but also for higher order statistics.

In the European initiative PRUDENCE (Christensen et al., 2002; 2006) as many as 10 RCMs were applied to explore the uncertainties in regional climate change projections due to RCM formulation as well as GCM formulation, and scenario specification, as combinations of downscaling experiments from 3 different GCMs and two SRES scenarios were combined. This enabled some first rough quantitative estimates of the uncertainty in climate change projections due to these sources of uncertainty to be made (e.g. Deque et al., 2005).

As mentioned above, many RCMs have since TAR been run for periods of 30 years per time-slice. Few RCMs have even attempted transient experiments, run from some present-day climate through the whole 21st Century (e.g. Kwon et al., 2003). Transient RCM-runs improve the means for evaluating pattern-scaling techniques for regional studies, provide coherent regional climate projections for different time horizons and also facilitate regional-scale impact studies dealing with topics that are affected by the transience (e.g., ecosystems and forestry).

Climate change in the Arctic

The Arctic climate is characterized by a distinctive complexity due to numerous nonlinear interactions between and within the different components (atmosphere, cryosphere, ocean, land) which generate a variety of internal feedbacks. Sea ice plays, through the albedo-temperature feedback and feedbacks associated with humidity and clouds, a critical role for the Arctic climate. Sea ice, ocean and atmosphere are closely coupled to each other. Examples are the following: Changes in sea ice concentrations influence the surface heat fluxes and surface albedo, both affecting the atmosphere. In return, weather systems and surface heat flux changes impact the sea ice thickness by determining the thermodynamic growth and ice dynamics. Changes in the oceanic heat transport (e.g., driven by atmospheric circulation pattern changes) affect the sea ice thickness and concentration and hence the climate sensitivity (e.g. Steele et al., 2004).

Strong low-frequency variability is evident in various atmosphere and ice parameters (Polyakov et al., 2003ab), complicating the detection and attribution of Arctic changes. The natural decadal and multi-decadal variability, e.g., as possibly expressed by the warming in the 1920s–1940s (Johannessen et al., 2004; Bengtsson et al., 2004) followed by cooling until the 1960s, is in the Arctic large. In both models and observations, the interannual variability of monthly temperatures is a maximum in high latitudes (Räisänen, 2002).

Natural atmospheric modes of variability on annual and centennial time scales play an important role for the Arctic climate. Such modes include for example the NAO/AO and the North Pacific Index. The influence of NAO/AO on Arctic temperature is directly opposed in the western and eastern Arctic. A positive NAO/AO index is associated with warmer and wetter winters in northern Europe and Siberia and cooler and drier winters in western Greenland and north-eastern Canada. A positive AO index is associated with warmer temperatures in Alaska and a reduction of blocking events and the associated severe weather throughout Alaska. The North Pacific Index is a more regionally restricted signal. In its negative phase, a deeper and eastward shifted Aleutian low pressure system advects warmer and moister air into Alaska.

Present climate: regional simulation skill

The above described complexity includes many processes that are still poorly understood and thus pose still a challenge for climate models as also concluded by the Arctic Climate Impact Assessment (ACIA, 2005). Generally, individual GCMs show still large biases in the simulated Arctic temperature, precipitation, and sea ice. Substantial across-model scatter exists. But the evaluation of the model simulations in the Arctic generally contains a relatively high uncertainty as, except for the sea ice cover, the few available observations are sparsely distributed in space and time and the different data sets often differ considerably (Serreze and Hurst, 2000). This holds especially for the precipitation measurements with its problems in cold environments (Goodison et al., 1998; Bogdanova et al., 2002).

Few pan-Arctic atmospheric RCMs are in use. Notwithstanding their dependence on the boundary data used, they capture the geographical variation of temperature and precipitation in the Arctic more realistically than the GCMs. Further, driven by analyzed boundary conditions, RCMs tend to show smaller temperature and precipitation biases in the Arctic compared to the GCMs indicating that sea ice simulation biases and biases originating from lower latitudes contribute to the contamination of GCM results in the Arctic (Dethloff et al., 2001; Wei et al., 2002; Semmler et al., 2005). However, even under a very constrained experimental RCM design, there can be considerable across-model scatter in the simulations as shown by the ARCMIP experiment (Rinke et al., 2005.

Within ACIA (2005), an analysis of mean model ensemble bias was found to be relatively small compared to the across-model scatter. However, difference between the coldest and warmest model was large during most of the year. Over the Arctic Ocean, the across-model scatter shows the same seasonality as the bias and is consistent with the wide range of simulated sea ice margins from autumn to spring. The across-model scatter of annual and seasonal temperatures is generally larger than the interannual variability, but the key features of the spatial patterns are similar connected with the sea ice variability. Compared with previous models, the AR4 temperatures are more (less) consistent across the models in winter (summer) (Chapman and Walsh, 2005).

There is considerable agreement between the modelled and observed interannual variability both in magnitude and spatial pattern of the variations and the seasonality of the variability is also well-simulated (Chapman and Walsh, 2005). A large subset of AR4 models are able to replicate such major warming events as occurred in the Arctic in the past (Wang et al., 2005).

The AR4 model simulated monthly precipitation varies substantially among the models throughout the year. To give one example, the simulated mean July precipitation averaged over the area north of 70°N ranges from 0.7 mm/d to 1.2 mm/d (Kattsov et al., 2005). But, the model ensemble mean is throughout the year within the range between different data sets which indicates an improvement compared to earlier overestimation (Walsh et al., 2002; ACIA, 2005). The seasonal cycle of the model ensemble mean is again in agreement with the observed climatology, but the mean precipitation is improved from autumn to spring (Kattsov et al., 2005). The ensemble mean bias varies with the season and remains greatest in spring and smallest in summer. The bias pattern (positive bias over the central Arctic and particular over the North American sector, negative bias over the north-eastern North Atlantic and eastern Arctic) persists throughout the year and can be partly attributed to coarse orography, biased atmospheric circulation (i.e., storm tracks) and sea ice cover.

There is a considerable range of Arctic sea ice conditions in present-day AR4 simulations, particularly on the regional scale (Arzel et al., 2005; Zhang and Walsh, 2005) as in previous CMIP simulations. However, the Arctic- and multi model averaged sea ice extent and its trend are in agreement with observations. The AR4 models generally underestimate sea ice concentrations in the interior Arctic while they overestimate it in the Greenland and Barents Seas. The spatial distribution of the simulated sea ice thickness varies considerably among the models.

Climate projections

The maximum northern high-latitude warming ("polar amplification") is consistently found in all GCM intercomparison studies (e.g. Serreze and Francis, 2005). The simulated annual mean Arctic warming exceeds the global mean warming by 2 times in the AR4 models. Comparable magnitudes are known from previous studies (Holland and Bitz, 2003, ACIA, 2005). At the end of the 21st century, the annual warming in the Arctic is estimated to be 5°C (with a considerable across-model range of 2.8–7.8°C between the lowest and highest projection) by the AR4 models under the A1B scenario. Larger (smaller) mean magnitudes are found for the A2 (B1) scenario with 5.6°C (3.4°C) but with a same across-model range of ~4°C. Comparable magnitudes have been found in earlier estimates (ACIA, 2005). The across-model and across-scenario variabilities in the projected temperatures are comparable.

The largest (smallest) warming is projected in autumn/winter (summer) both over ocean and land (Figure 1). But, the seasonal amplitude of the temperature change is over ocean (7°C) much larger than over land (4°C) due the presence and melt of sea ice over the ocean in summer keeping the temperatures close to the freezing point. The Arctic Ocean region is generally warmed more than the land area (except in summer). The range between the individual simulated changes is large. For Arctic land by the end of the century, the warming ranges from 3.7°C to 9.5°C in winter, and from 1.6°C to 5.5°C in summer under A1B scenario. The across-model scatter can be attributed to the different description of the physical processes in the individual models, whereby the present-day sea ice state is one important factor. Internal variability, which is large particularly over land, contributes also to the across-model differences.

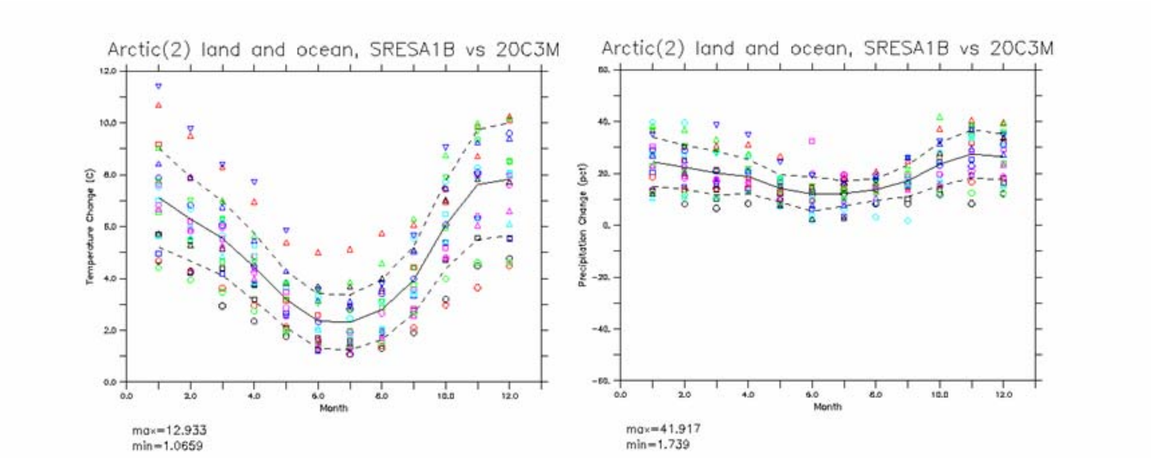

Figure 1 Annual cycle of monthly mean Arctic temperature and percentage precipitation changes (averaged over the area north of 60°N) (for 2079–2098 minus 1979–1998 under the A1B scenario). Solid lines are the AR4 model ensemble mean, dashed lines represent the one standard deviation across the different models, and the colored points are the individual model realizations.

The annual temperature response pattern is characterized by a large warming over the central Arctic Ocean (5–7°C) and caused by the warming in winter and autumn associated with the reduced sea ice (Figure 2). The maximum warming is near the Barents Sea where the present-day model bias is also greatest. Further, a region of reduced warming (<2°C, slight cooling in several models) is projected over the northern North Atlantic which is also consistent among the models. This is caused by deep ocean mixing, weakening of the THC and reduction of heat transport into these regions and is in agreement with earlier studies (Holland and Bitz, 2003).

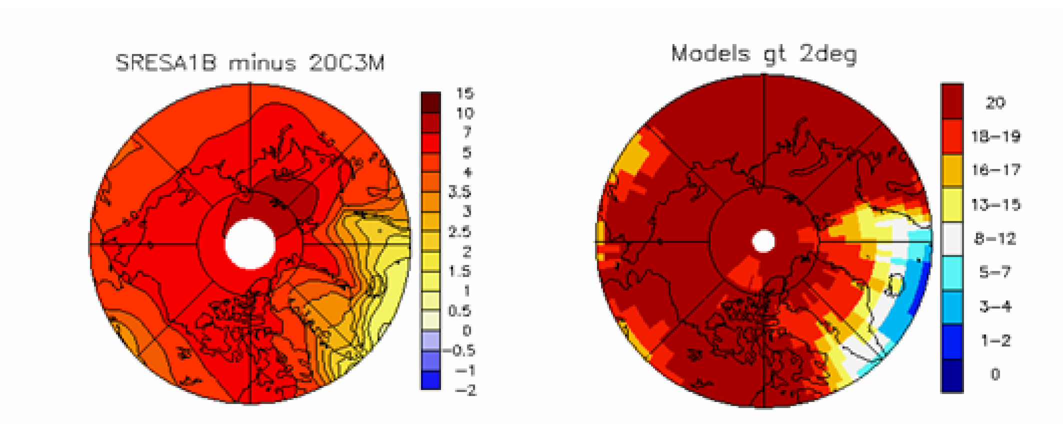

Figure 2 Annual surface temperature change (°C) from 1979–1998 to 2079–2098 in the Arctic under the A1B scenario. (a) mean over all 20 AR4 models, (b) number of AR4 models that generate a warming greater than 2°C.

Within the first half of the 21st century, the projected temperature changes do not exceed the internal variability, i.e. are not significant (Chapman and Walsh, 2005). At the end of the 21st century, the projected changes over the Arctic Ocean are clearly discernable from natural variability. However, the projected large warming over northern Alaska in winter cannot be discerned from natural variability as the simulated (and observed) temperature variability in this region is so large (Chapman and Walsh, 2005).

The regional temperature responses are largely determined by changes in the synoptic circulation patterns. The AR4 models project in winter circulation changes consistent with an increasingly positive AO which corresponds to warm anomalies in Eurasia and western North America, while in summer, circulation patterns are more likely that favor warm anomalies north of Scandinavia and extending into the eastern Arctic and cold anomalies over much of Alaska (Cassano et al., 2005). But, this projected cooling is in disagreement with the recent strong warming trend in Alaska (ACIA, 2005; Hinzman et al., 2005) indicating a decreased confidence in the summer projections (associated with the models inability to accurately simulate the present-day summer synoptic patterns).

The AR4 models simulate a consistent general increase in precipitation over the Arctic at the end of the 21st century. The precipitation increase is robust among the models and qualitatively well understood, attributed to the projected warming and related increased moisture convergence (ACIA, 2005; Kattsov et al., 2005). The spatial pattern of the projected change shows greatest percentage increase over the Arctic Ocean (30–40%) and smallest (and even slight decrease) over the northern North Atlantic (<5%). The correlation between the temperature and precipitation changes over the Arctic Ocean is strong and the magnitude of the precipitation response is consistent among the models (ca. 5% precipitation increase per degree warming).

By the end of the 21st century, the projected change in the annual mean Arctic precipitation varies between the lowest and highest projection from 10% to 29%, with an AR4 model ensemble mean of 19% for the A1B scenario. Larger (smaller) mean magnitudes are found for the A2 (B1) scenario with 22% (13%) but with a same inter-model range. The differences between the projections for different scenarios are small in the first half of the 21st century, but increase after. However, towards the end of the 21st century, the differences between different scenarios are smaller than the across-model scatter (ACIA, 2005; Kattsov et al., 2005). For each scenario, the across-model scatter of the projections is substantial, but smaller than the across-model scatter under present-day conditions (Kattsov et al., 2005). The percentage precipitation increase is largest in winter and autumn and smallest in summer, accordingly to the projected warming (Figure 1).

The range between the individual simulated changes is large. For Arctic land by the end of the century, the precipitation increase ranges from 13% to 44% in winter and from 3% to 21% in summer under A1B scenario (Table 11.3.8.1). The differences increase rapidly as the spatial domain becomes smaller (ACIA, 2005). To give one example, 6 AR4 models project a decrease in summer precipitation for the Ob basin, while the rest of the 14 models project an increase under the A2 scenario at the end of the 21st century (Kattsov et al., 2005). The local precipitation anomalies are determined largely by changes in the synoptic circulation patterns. During winter, the AR4 models project a decreased (increased) frequency of occurrence of strong Arctic high (Icelandic low) pressure patterns which favor precipitation increases along the Canadian west coast, southeast Alaska and North Atlantic extending into Scandinavia (Cassano et al., 2005). The regional precipitation patterns, e.g., along the North Atlantic storm track and close to complex topography and coast lines are more detailed in RCM simulations due to the higher resolution (ACIA, 2005).

The across-model scatter in the precipitation projections can be attributed to the different description of the physical processes in the individual models and to internal variability. At end of the 21st century under A1B scenario, the AR4 model averaged signal-to-noise ratio starts exceeding the factor 2 in the annual mean and in winter/autumn, and mostly over ocean (Kattsov et al., 2005), indicating that the projected increase is discernable from natural variability. However, local precipitation changes (particularly in the Atlantic sector and generally in summer) remain difficult to discern from natural variability even at the end of the 21st century (ACIA, 2005; Kattsov et al., 2005).

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