ICARP II – SCIENCE PLAN 9

MODELING AND PREDICTING ARCTIC WEATHER AND CLIMATE

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PREFACE

The Second International Conference on Arctic Research Planning (ICARP II) was held in Copenhagen, Denmark from 10 November through 12 November 2005 and brought together over 450 scientists, policy makers, research managers, indigenous peoples, and others interested in and concerned about the future of arctic research. Through plenary sessions, breakout sessions and informal discussions, conference participants addressed long-term research planning challenges documented in twelve draft research plans. Following the conference drafting groups modified the plans to reflect input from the conference discussions and input from the ICARP II web site. This science plan is the culmination of the process.

ICARP II Science Plans

Science Plan 1	Arctic Economies and Sustainable Development
Science Plan 2	Indigenous Peoples and Change in the Arctic: Adaptation, Adjustment and Empowerment
Science Plan 3	Arctic Coastal Processes
Science Plan 4	Deep Central Basin of the Arctic Ocean
Science Plan 5	Arctic Margins and Gateways
Science Plan 6	Arctic Shelf Seas
Science Plan 7	Terrestrial Cryospheric & Hydrologic Processes and Systems
Science Plan 8	Terrestrial and Freshwater Biosphere and Biodiversity
Science Plan 9	Modeling and Predicting Arctic Weather and Climate
Science Plan 10	A Research Plan for the Study of Rapid Change, Resilience and Vulnerability in Social-Ecological Systems of the Arctic
Science Plan 11	Arctic Science in the Public Interest
Background Document	Contaminants

9.1. Background and Strategic Areas of Interest

9.1.1. The Problem

Present climate models suggest that the greatest human-induced warming will occur in the Arctic, but there are considerable variations in the magnitude of the warming projected by the different models. There are also considerable variations in timescales involved, ranging from years to several decades for different projections by the same model, suggesting large natural variations. The challenge is to identify and model the important components of the climate and the environment and to use this to assess and predict changes in the arctic climate system and the environment, due to both natural and anthropogenic effects. Owing to the complexity of the climate system this will require modeling and prediction studies that include interactions between physical, chemical, and biological processes in the atmosphere, oceans, cryosphere, land surfaces, and the biosphere over timescales ranging from hours to centuries. These earth system models will serve as drivers for a number of detailed application studies relevant for a broad arctic research program, such as considered within the ICARPII process.

A key scientific focus is to clarify the robustness of arctic climate change and the feedback processes responsible for the large climate variations. It is necessary to better understand and quantify the extent to which arctic climate change is due to regional or global processes. Also, to quantify the likelihood of “abrupt events”, particularly those important to arctic climate stability, such as marked changes in the North Atlantic thermohaline circulation, rapid melting of arctic sea ice, and the risk of a rapid reduction in the Greenland Ice Sheet.

There has been a big reduction in arctic sea-ice extent over the last 30 years (Figure 9.1). There are also some indications of a reduction in sea-ice thickness over this period. Climate models project that arctic sea ice will largely disappear in summer towards the end of the 21st century. A key focus will be to improve the understanding of this reduction and to identify the extent to which this reduction is related to natural variability or to anthropogenic effects.

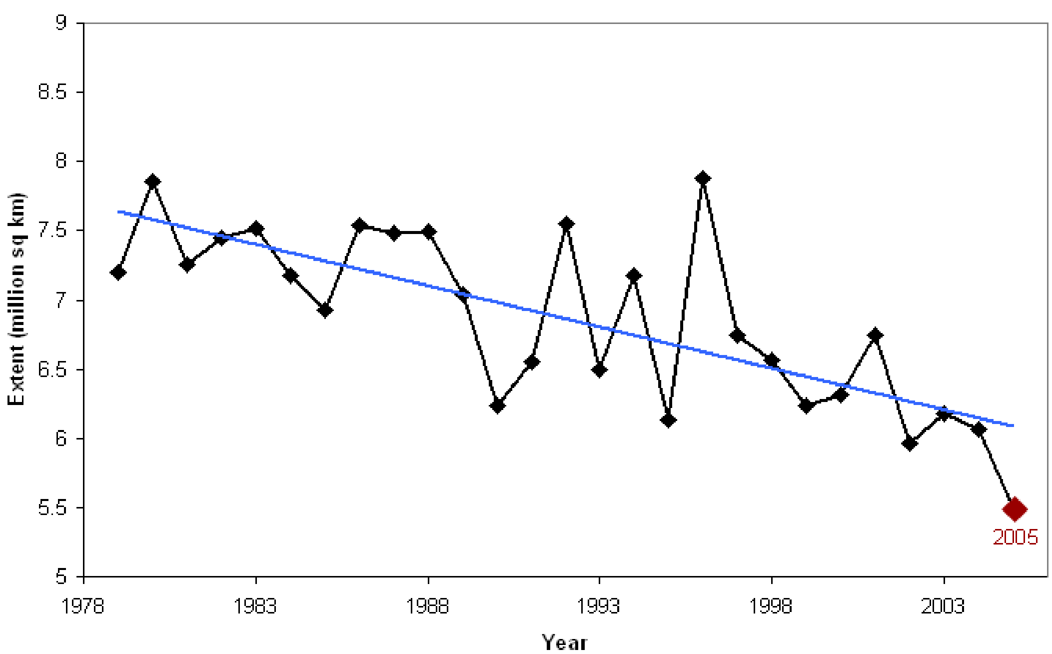

Figure 9.1. Arctic sea-ice extent in September for the period 1979 to 2005 (The National Snow and Ice Data Center, CIRES, Boulder, United States).

There have been large annual and interannual variations in stratospheric ozone levels in the Arctic, but there has also been an indication of a general downward trend in late winter concentration coinciding with a trend towards unusually low temperatures in the stratospheric polar vortex. A key focus is to determine the extent of the natural variability to better clarify and identify any long-term trend. How much of the stratospheric cooling can be attributed to greenhouse gases, how much is due to ozone depletion, and how much is due to changes in circulation? To what extent can stratospheric changes, as have been shown for the Antarctic, influence the arctic troposphere due to dynamical processes?

There are signs of diminishing permafrost in several parts of the Arctic but this decrease is not as rapid as expected. A key focus will be to clarify the extent and rate of permafrost reduction, to improve its modeling and to increase understanding of its consequence for the biosphere and its socio-economic effects in general. The projected warming of the Arctic during the 21st century will affect the carbon cycle and possibly also the methane cycle. This emphasizes the need to incorporate interactive bio-geochemical cycles in the climate models.

Modeling and prediction experiments are key tools to address and better understand these issues. Modeling capabilities have evolved significantly due to rapidly increasing computing power and ongoing improvements in physical representations. Weather prediction models can now incorporate mesoscale processes even at global scales and climate models in centennial integrations can resolve synoptic scale weather systems. Modeling and prediction of weather and climate is presently undergoing a major change towards integrated systems used both for weather and climate prediction and for monitoring where different model components are systematically integrated into earth system models. This is a key objective for the modeling activity within the World Climate Research Programme and the International Geosphere-Biosphere Programme Integrated systems for modeling and data-assimilation will play a central role for systematically deploying and using observations in prediction and monitoring.

9.1.2. Different Timescales

As modeling and prediction depend strongly on the timescale involved it is necessary to separate modeling and prediction according to different time-regimes. Although the emphasis in this ICARP II science plan is on the Arctic, models have to be global, but they would include nested models or models with higher resolution in the Arctic. To achieve predictions and to identify better the risk of extreme events ensemble modeling will be required for all timescales.

Prediction on timescales shorter than a season is essentially an initial-value problem where the main emphasis is on an accurate initial state using advanced data-assimilation and detailed modeling at high vertical and horizontal resolution. The overall strategy as outlined in the THORPEX program will be followed (THORPEX, 2003).

Modeling and prediction on seasonal and interannual timescales is also an initial-value problem but one requiring advanced land/ocean/atmosphere-coupled models. Predictive skill will vary considerably but is likely to generally be better in cases with pronounced sea surface temperature and sea-ice anomalies.

Prediction experiments for the next few decades require high-resolution general circulation models (GCMs). Together with the projected warming trend, predictions are expected to be strongly influenced by internal variability (Polyakov and Johnson, 2000; Polyakov et al., 2002). The main purpose of the experiments will be to determine the range of the predicted variations in arctic climate, over for example the next 25 years. This will serve as guidance for arctic climate assessment in a period during which anthropogenic emissions and thus forcing can be reasonably accurately estimated.

Prediction experiments for the next few centuries would be an appropriate component of the Intergovernmental Panel on Climate Change (IPCC) modeling experiments using the emission scenarios proposed under that program. The main emphasis will be assessment of arctic climate change over the next few hundred years, including evaluations of possible abrupt events. Studies of past climates will help toward understanding such events.

Studying and simulating the past climate is another important component that will help understand the evolution of the arctic climate. The last couple of thousand years are particularly interesting in this respect, since there are several sets of proxy data as well as a reasonable knowledge of the external forcing (orbital forcing and volcanic forcing).

9.1.3. Priorities

Observing systems in the Arctic are insufficient and major efforts are needed in many areas, including the provision of alternatives for the recent loss of upper air stations. Improved utilization of satellite data is part of the solution.

This ICARP II science plan addresses modeling and prediction of past, present, and future weather and climate on timescales ranging from days to a couple of thousand years. The reason for this time frame is the ICARP II cover "The Arctic System in a changing World" with an emphasis on the likely evolution over the next 100 years. It is also recognized that there have been large variations in past climates and that the processes behind these variations may also be of relevance in relation to anthropogenically induced global warming.

In general this ICARP II science plan covers only those processes and components that are expected to provide a first order feedback on the rest of the climate system on timescales up to about 100 years. It is well known that processes related to ice sheets and glaciers and bio-geochemical processes do feedback on these timescales. However, since the cryosphere is addressed by ICARP II Science Plan 7 it is suggested that dynamical and thermodynamical ice sheet modeling be addressed there. Similarly, it is suggested that biospheric modeling be addressed by ICARP II Science Plan 8. This implies clear overlaps between the three ICARP II science plans.

Evaluation of the actual – and still unknown – level of potential predictability on all these timescales in the Arctic is given very high priority. It is necessary to better understand whether weather and climate in the Arctic is more (or less) predictable than for other parts of the globe.

An activity of high priority in relation to this ICARP II science plan is to better explore the predictive skill of current models and forecasting systems on timescales ranging from days to decades. The capabilities of current operational systems are not yet fully explored in the Arctic.

9.2. Weather Prediction in Polar Regions

The accurate prediction of weather systems in polar regions is critical to numerous societal, environmental, and economic applications. High impact weather events in polar regions include spring thaws, sea-ice movement, and severe winter cyclones (including both synoptic-scale and polar lows) and katabatic flows resulting in strong winds and blizzards, high seas, and heavy precipitation as defined by their impact on public safety, fisheries and fishery management, activities of the indigenous arctic populations, wildlife, energy production, and transportation. Climate change research provides additional motivation for improving the treatment of polar processes in numerical models. For example, current predictions of climate change indicate that some of greatest atmospheric warming is likely to occur at higher latitudes and with the potential to reduce sea-ice cover substantially. Research questions include whether this increase in open water will modify the frequency, location, and intensity of cyclonic storms. Accurate modeling of the location, frequency, and intensity of these storms and their associated precipitation, surface winds, and cloud cover is necessary to predict the potential societal, economic, and environmental impacts that may accompany such changes. Systematic modeling errors will translate directly into uncertainty in the prediction of climate change in polar regions.

A particular concern for weather prediction in the Arctic is the state of the observing system. In recent years there has been a significant reduction in high latitude upper air observations. Satellite observations have a limited coverage in the Arctic compared to lower latitudes and vertical sampling is compromised by the existence of sharp boundary layer inversions. Special efforts are needed to optimize the arctic observing system and it is recommended to use data-assimilation experiments towards achieving such an objective.

9.2.1. The THORPEX Program and its Relevance for Arctic Weather Prediction

THORPEX (The Observing System Research and Predictability Experiment) is an international ten-year program developed and implemented under the World Meteorological Organization (THORPEX, 2003). The scope of THORPEX is similar to that of the Global Atmospheric Research Program (GARP) undertaken in the 1970s, or more recently the International Polar Year (IPY) as both efforts represent periodic, major international research efforts to advance understanding of key aspects of the earth system. The world's meteorological community, for example, have twice banded together to conduct major global research efforts: the International Geophysical Year in 1957-58, which included a major polar effort, and GARP, which began in the late 1960s later to be followed by the World Climate Research Program (WCRP). The aim of the THORPEX program is to accelerate improvements in the accuracy of 1-day to 2-week high-impact weather forecasts for the benefit of society and the economy. THORPEX will achieve this through interrelated research components that include: data assimilation and observing strategies; predictability and dynamic processes; observing systems; and societal and economic applications.

<u>Understanding two-way interactions between polar and sub-polar weather regimes</u>. Research on understanding two-way interactions between polar and sub-polar weather regimes aligns with the THORPEX focus on "global-to-regional influences on the evolution and predictability of weather system" and the IPY objective of "understanding polar-global teleconnections on all scales, and the processes controlling these interactions". THORPEX/IPY will address high-impact weather forecasts, predictability, and increased knowledge of related physical and dynamical processes associated with polar and sub-polar interactions.

<u>Development, testing and refinement of coupled models designed to simulate and predict conditions for the polar earth system</u>. Accurate coupled modeling of the polar region presents unique challenges including an accurate depiction of upper ocean circulation in the polar gyres and representing the large spatial and temporal variations in the sea-ice field. Coupled models are critical to the numerical weather prediction goals of THORPEX and the climate change issues of IPY. For example, variations in the sea-ice field can influence the atmosphere in various ways: significant amounts of heat and moisture can be injected into the boundary layer over open leads, and changes in the sea-ice margin will alter regional baroclinicity and hence the strength and track of cyclones. Efforts to improve data assimilation in the polar regions, as discussed previously, will directly benefit the quality of these analyses. It is likely that these efforts will need to be coupled with advances in model physics, particularly regarding components of the water cycle in polar regions.

<u>Assessment of skill in the prediction of polar to global high impact weather events for different observing strategies at higher latitudes</u>. Research topics would include: evaluating the impact of the supplementary IPY measurements; evaluating various targeted observing strategies; assessing the contribution of Siberian radiosonde networks to numerical weather prediction and whether alternative network configurations should be considered; and increasing knowledge of the errors and challenges associated with obtaining good satellite, in-situ and surface-based remote sensing observations in polar regions so that improved observing systems and strategies can be developed in the future.

<u>Demonstration of the utility of improved utilization of ensemble weather forecast products for high impact weather events and for IPY operations, when applicable</u>. High impact events for the economy, environment, and society include spring thaw, poor visibility, sea-ice movement, and severe winter cyclones resulting in strong winds, high seas, and heavy precipitation. Examples of polar influences at

mid-latitudes include cold polar air outbreaks, extratropical cyclones, and lake effect snowfall. THORPEX activities will include an evaluation of the concept of the THORPEX Interactive Grand Global Ensemble (TIGGE) prediction system, for providing ensemble forecasts tailored for polar weather events and effects of polar processes on sub-polar weather. This effort involves evaluating the utility of a coordinated multi-national ensemble forecast system and associated research opportunities in areas of predictability, data assimilation, observing strategies, and observing system studies.

Recommendations on the design of the Global Observing System in polar regions for weather prediction and climate monitoring. THORPEX research will evaluate improvements in forecast skill associated with polar observing strategies as well as the societal benefits of any associated improvements in forecast skill. Thus, THORPEX is well positioned to make recommendations on which IPY legacy instrumentation will be most useful from the weather perspective. Such instrumentation will prove beneficial to society from the perspective of weather prediction and climate monitoring.

Field campaigns. To assist in accomplishing these research goals, THORPEX/IPY will conduct field campaigns during the IPY intensive observing period. A key aspect will be to include rawinsonde or remote sensing capability on polar research vessels deployed for the IPY.

9.2.2. Expected Outcome

The activities of THORPEX/IPY are expected to result in improved operational forecasts of polar-related high impact weather events. The results of such investigations will advance data assimilation techniques and the modeling of physical dynamic and cryospheric processes, and will provide better guidance for optimized observing systems and more advanced prediction strategies. This could lead to accelerated operational production of mesoscale weather forecasts at ultra-high resolution (1-2 km), through the implementation of a coupled atmosphere-ice-ocean system for both the Arctic and Antarctic during the IPY. These products would be of immense value for planning field experiments (flights, cruises, transects) as well as for emergency response situations. The data assimilation subsystems would produce real time high-resolution analyses of surface, atmospheric, and oceanic conditions, and would allow IPY investigators quick turnaround on the value and impact of their data sets. Conversely, supplementary data collected during the IPY would be fed immediately to the National Meteorological and Hydrological Service (NMHS) centers and would allow immediate improvements in advanced operational products.

Improved operational and research modeling capabilities would be an important legacy of the THORPEX/IPY due to the numerous societal, economic, and environmental user needs that result from high-impact weather in the polar regions.

9.3. Seasonal and Interannual Timescales

The atmosphere plays a central role in climate variability on seasonal and interannual timescales, because it acts as a fast global communicator between remote geographical regions. Atmospheric teleconnection patterns exert a strong influence on horizontal and vertical exchange processes of the coupled climate system. Seasonal variations are superimposed on interannual and decadal scale processes linked to the internal variability of the atmosphere and anthropogenic influences. Climate variations on seasonal and interannual timescales are a result of:

- Internal variability such as preferred modes of the troposphere-stratosphere circulation (North Atlantic Oscillation (NAO)/ Arctic Oscillation AO), Pacific-North American Oscillation (PNA), and other modes of the coupled atmosphere-ocean-sea-ice-land system and transitions between such circulation regimes.
- Global circulation patterns and regional feedbacks such as sea-ice albedo, cloud-water vapor, and cloud-radiation-aerosol feedbacks.

- Externally and anthropogenically caused climate variability due to increasing levels of trace gases and variations in ozone, volcanic and anthropogenic aerosols, and possible changes in solar radiation.

Observational studies show evidence for the existence of multiple regimes for the northern hemisphere (Deser et al., 2000). Climate models are able to capture these regimes. The regime concept appears valid for anthropogenic influenced climate change. Studies with simple nonlinear atmospheric models, data analyses, and analyses of model runs with increased levels of greenhouse gases suggest that response patterns of external forcing generally project onto the natural variability modes, but the probability density of the preferred circulation regimes may change. Whether some of the modes of atmospheric circulation have predictive skill, it is still an open question if any useful predictability on seasonal timescales in a general sense exists in the Arctic (Rinke et al., 2006).

Atmospheric circulation regimes are a basic concept for understanding climate variability, not only at the global scale but also for the arctic region. Atmospheric variability is characterized by a limited number of typical large-scale flow patterns, which generally occur in preferred geographical regions. Within this framework, low-frequency climate variability can arise due to transitions between atmospheric regimes and is manifested, primarily, as changes in the frequency of occurrence of the preferred circulation regimes.

The WCRP has established a strategic framework (COPES - Coordinated Observation and Prediction of the Earth System), (WCRP, 2005). One of the objectives of the strategic framework is to produce comprehensive, integrated datasets describing the evolution of components of the climate system over recent decades. This will be accomplished with the help of advanced data assimilation. In this process, background states from a model that simulates one or more components of the system are adjusted to fit the historical observational record in a way that is consistent with statistical and physical constraints. The quality of reanalysis products depends on the realism of the assimilating model, on the accuracy and density of the available observations, and on the way model states and observations are merged. Quality may thus vary from one climate component to another, from one region to another, and between periods with different observational coverage.

9.3.1. Seasonal and Interannual Predictions

A realistic aim of seasonal prediction is to predict anomalies in large-scale circulation patterns, presumably driven by anomalies in sea surface temperatures (SST), sea-ice distribution, land surface properties or stratospheric ozone. The slow fluctuations of SST on a seasonal time scale can be predicted to some extent, up to about six months ahead. Links between SST and atmospheric circulation are realistically represented in coupled models of the atmosphere-ocean-sea-ice system, which form the basis of present seasonal prediction systems. The strongest links between SST patterns and trends in seasonal weather are found in the tropics and seasonal forecasting is most successful in these regions. The best-known links are those associated with the ENSO (El Niño – Southern Oscillation) phenomenon, which is manifest as a warming (or cooling) of SST in the tropical Pacific that occurs on average every three to five years. ENSO can disrupt normal weather patterns around the globe. Although the strongest links between SST and seasonal weather are found in the tropics, there is good evidence that similar, if weaker, links are present in other parts of the globe. The Arctic may have potential predictability on seasonal timescales due to feedback of arctic sea-ice and snow cover.

Because the link between weather and SST is best detected in long-term weather averages, and because the uncertainty in forecasts generally increases as the forecast range increases, seasonal forecasts look rather different compared to NWP (Numerical Weather Prediction) daily forecasts. The key differences are that forecasts are for conditions averaged over a season and are best stated in probability terms. There are three sources of prediction errors:

- uncertainty due to nonlinearities and instabilities. This implies strong dependence on the initial conditions;

- inadequacies of the observing systems and imperfect spatial coverage, leading to imprecise initial conditions; and
- sub-optimal coupling between the model equations and parameterizations and inadequate horizontal and vertical resolution leading to aliasing effects.

The combination of nonlinearities and instabilities limits skillful forecasts even of the largest scales of motion, the long planetary waves as errors on the smallest spatial scales successively contaminate the largest planetary scales in about two to three weeks.

However, some aspects of atmospheric flow may nevertheless be predictable on longer, for example, seasonal timescales. This is particularly the case if they are forced by slowly changing influences from the surface boundary, for example SST anomalies. GCMs have been used to perform multiple simulations, differing only by very small perturbations in the initial conditions. The results show the growth and saturation of errors in sea level pressure for winter and summer; winter errors grow more rapidly than summer errors. The errors are greatest in mid-latitudes, where baroclinic activity is greatest. The errors are smaller in the tropics. Even after a month some skill can be found in the large-scale patterns.

9.3.2. Challenges

Feedback mechanisms between dynamical, chemical, and radiative processes of the tropo-stratosphere have the potential to change the teleconnection patterns of the atmosphere. The roles of topographically forced planetary waves, the contribution of baroclinic processes and wave-mean flow interactions and coupling processes with the stratospheric vortex need to be more thoroughly investigated.

The variability of the Arctic Oscillation (AO) results mainly from the internal dynamical processes of the atmosphere. Such variability results form strong nonlinear interactions between the time-mean flow and the planetary or baroclinic wave systems under the influence of external radiative forcing. Efforts are needed to clarify the nonlinear interactions of dynamical changes connected with the AO and chemical changes in the stratospheric ozone layer. The stratosphere has gradually cooled over the last decades, leading to a stabilization of the polar arctic vortex. In this respect, the relation between greenhouse gases and ozone depletion needs to be better understood.

The stratosphere responds strongly to changes in the tropospheric circulation and temperature, but may also trigger tropospheric changes. Therefore not only long-term changes associated with increasing levels of greenhouse gases, but also dynamical variations on timescales from years to a few decades must be considered. The large-scale circulation patterns and seasonal and decadal scale changes should be investigated to improve the physical-chemical description of the coupled tropo-stratospheric system and to understand the interactions.

Circulation changes on seasonal timescales are linked to internal dynamical changes due to regime transitions and regional feedbacks, for example, surface-soil interactions and coupling to atmospheric boundary conditions such as orography and SST or sea-ice anomalies influencing blocking patterns and storm tracks. Seasonal predictions are the key to understanding decadal-scale variability.

The summer heat wave over Europe in 2003, for example, was mainly due to a large-scale atmospheric circulation anomaly leading to spring dryness. This triggered a quasi-stationary high-pressure pattern with reduced cloud cover, leading to more solar radiation at the surface, stronger heat fluxes into the atmosphere, further drying of the soil, reduced cloud cover providing higher surface temperatures and less favorable conditions for precipitation.

The middle atmosphere responds strongly to changes in the tropospheric circulation and temperature. However, changes in the middle atmosphere also affect the troposphere through influences on the AO/NAO (Baldwin et al., 2003). The mechanism of this downward impact and two-way feedback between the tropo-stratosphere is not fully understood but may be caused by the interaction of atmospheric long stationary and transient waves with the mean flow. The apparent downward propagation of these circulation patterns raises possibilities for seasonal predictions. Better knowledge of the state of the stratosphere is likely to improve tropospheric predictions. It is important to document stratospheric ozone and tropospheric aerosol anomalies.

9.3.3. Summary

The occurrence of heavy rainfall and extreme weather events is largely associated with synoptic weather systems, which are often linked through atmospheric modes and circulation regimes such as the AO. The predictability of the NAO and AO is a major challenge with the potential to improve long-range forecasts. The predictability of any dynamical system strongly depends on the knowledge of its initial state. There is a need to improve the initial conditions for NWP, especially in the Arctic. What are the most critical values for the initial fields? Can critical areas be identified and improved by targeted observations? State predictability can be enhanced if the atmosphere-soil interactions and atmosphere-ocean-sea-ice interactions are accurately included in coupled models. Different studies indicate that a multi-model ensemble approach is promising.

Successful prediction of climate anomalies on seasonal to interannual timescales is not only of scientific interest but is also of considerable public interest. The climate system is highly nonlinear but complex chaotic systems can nevertheless exhibit considerable predictability. Non-linear interactions in the atmosphere and the coupled system can generate low-frequency variability, which can be projected on typical atmospheric modes such as the AO (Schneider et al., 2003) and some of this may be predictable.

9.4. Arctic Climate Projection for 2005 to 2030

9.4.1. State of Science

Recent synthesis reviews based on instrumental records provide a reasonably coherent portrait of arctic and boreal change, indicating that the last few decades have shown strong warming over northern Eurasia and North America, reduced arctic sea-ice extent and thickness, marked changes in Arctic Ocean hydrography, reduced glaciers and snow cover, increased runoff into the Arctic, increased tree growth in northern Eurasia, and reduced tundra areas and thawing permafrost (e.g., ACIA, 2004).

The high northern latitudes are characterized by regional to hemispheric interannual to decadal scale natural variability modes, particularly during the winter months, December to March. The most prominent of the variability modes are the NAO and AO. The NAO is the dominant mode of climate variability in the North Atlantic region. Characterized by fluctuations in sea-level pressure between the Iceland and Azores regions, some of its impacts have been recognized for centuries. This is no surprise as storminess, temperature and precipitation in Northeastern America and Europe are related to the NAO. A high NAO index is associated with relatively mild, wet conditions in northern Europe and relatively cool, dry conditions in southern Europe, with the opposite situation the case under a low NAO index.

The NAO is closely related to the annular AO. The AO pattern in sea-level pressure is similar to that of the NAO in the Atlantic region, but is more hemispheric in extent, possessing a high degree of zonal symmetry. Past research has established that most of the NAO/AO variability at interannual timescales arises from processes internal to the atmosphere. The growth of weather systems in the North Atlantic storm track, and interaction between these systems and the larger scale mean flow, are key processes. It is also possible that northern hemisphere snow cover (i.e., albedo) anomalies amplify NAO/AO related climate anomalies on annual timescales Thus, unlike ENSO the NAO is fundamentally an atmospheric phenomenon, generated and manifested in the troposphere. However, its behavior, especially on longer timescales, can be modified by interactions with the ocean and the stratosphere. Recent work suggests that there may be an important two-way coupling between the NAO/AO and the Atlantic Ocean Meridional Overturning Circulation on the multi-decadal timescale (e.g., Schiller et al., 1997).

Many of the observed changes in the arctic environment summarized above can be related to the general rise in the AO/NAO from low values in the late 1960s and early 1970s to high values from the late 1980s to mid-1990s. During the first part of the 21st century the NAO has returned to low values. However, the high northern latitudes also saw a strong warming in the 1930s and 1940s, particularly pole ward of 60º N. This warming is comparable in amplitude to the observed present-day warming, although the recent warming is quite different in having a global expression (Johannessen et al., 2004). Multi-century control integrations with coupled climate models can simulate warming signals quantitatively similar to the 1930-40 warming, indicating that they are an inherent property of the climate system (Bengtsson et al., 2004).

Given the prominent natural variability in high northern latitudes, there are two central questions in addressing the evolution of climate for the period 2005 to 2030: Is it possible to uniquely identify a global warming signal against the expressions of existing natural variability? Is it possible that global warming may change the time-space characteristics of the high-latitude natural climate variability modes?

It is likely to be difficult to isolate an anthropogenic signal against natural climate fluctuations in the arctic region over the next few decades, such as the period 2005 to 2030. There are two main reasons for this. First, tailored analyses of 19 coupled climate models indicate that the ratio between anthropogenic and the natural variability noise is low. Second, model differences are expected, partly due to the non-linear effect snow, sea ice, clouds and aerosols have on the climate system, and partly due to systematic model deficiencies.

9.4.2. Observational Issues

Four observational components are needed: observations for evaluating model systems over the time period of the instrumental record; proper knowledge of the present-day climate for initializing the model systems; observations to support the proposed process studies; and monitoring of key quantities of the climate system.

9.4.3. Overall Modeling Issues

Reliable realizations of the arctic climate system for the period 2005 to 2030 depend on the initial value of the climate state, and the quality of the applied model systems. Given the uncertainties in the initial climate state, the climate model deficiencies and the large degree of stochastic climate variability at high northern latitudes, a multi-model ensemble approach is needed. For greenhouse gas forcing, the IPCC scenario A1B could be given priority as a suitable middle of the line scenario.

9.4.4. Deliverables

Model experiments will quantify the upper and lower bound of climate projections for the Arctic over the period 2005 to 2030. Climate parameters to be addressed include average and extreme values of temperature, wind, cloudiness, heat and freshwater flux components, sea ice extent and thickness, ocean circulation, ocean distribution of temperature and salt, state of the land surface and its hydrology including river run-off.

9.5. Arctic Climate in the 21st Century

For this timescale the emphasis will be on longer climate trends and assessing the extent to which trends depend on model characteristics and with internal model variability. Special attention will be devoted to risk assessments of abrupt or extreme events including rapid melting of sea ice and rapid changes in the thermohaline circulation. The IPPC A1B climate scenario (see section 9.4.3) could also be used here.

9.5.1. State of Science

A common finding from coupled atmosphere-ocean modeling studies of increasing greenhouse gas scenarios is that anthropogenic global warming will be enhanced at northern high latitudes, but greatest over the Arctic Ocean in autumn and winter. The predicted warming in the Arctic over the next 50 years based on a series of climate models and different climate scenarios is ~3-4 °C, or more than twice the global average. It is, however, important to note that there are large discrepancies between different model projections for the Arctic, ranging from essentially no change to a warming three to four times as strong as the global average warming.

The Arctic is a region with prominent natural climate variability. A crucial challenge is thus to identify and quantify the global warming signal against the impact of natural variability modes. However, the natural variability modes may change character as a result of global warming.

Reliable predictions of the climate state in the Arctic throughout the 21st century are crucially dependent on: long-term and high-quality observations; improved model systems carefully evaluated against available instrumental observations; and better understanding of high northern latitude climate variability modes and the interaction between high and lower latitudes.

9.5.2. Deliverables

Model experiments will quantify the likely upper and lower bounds of arctic climate conditions for the period 2030 to 2100. Climate parameters to be addressed include average and extreme values of temperature, wind, cloudiness, heat and freshwater flux components, sea-ice extent and thickness, ocean circulation, ocean distribution of temperature and salt, state of the land surface and its hydrology.

9.6. Past Arctic Climate

Paleo-climatic studies can contribute to the understanding of climate processes by examining past periods that were radically different from the present climate. Accumulating data point to a comparatively warm early Holocene in the Arctic – warmer than today, and the early Medieval Warm Period is in some instances regarded as a period of similar warmth as today. Detection of anthropogenic climate change in observations and validation of climate models and climate change feedback rely on improved understanding of natural climate variability. There are many IPY proposals from US and Europe that propose to assemble very high resolution data sets on paleo-climate for the last 2000 years. Some of these data are already in hand, but some will be obtained within the next few years. Such data will without doubt contribute to efforts to differentiate between natural and anthropogenic climate variability. Recent studies suggest larger multi-centennial natural variability in the past than previous reconstructions have indicated (von Storch et al., 2005).

Validation of the decadal to centennial timescale variability in coupled climate models is limited by the scarcity of long observational records. Proxy indicators of climate, such as tree rings and ice cores, can be used. Good estimation of natural climate variability is essential. Underestimation of natural climate variability by models may lead to false detections of climate change or erroneously low uncertainty estimates in predictions for the future. It is also important to include natural climate forcing factors in model control simulations due to solar variability and volcanic eruptions. Further quantification of uncertainties in the proxy data, and inclusion of natural climate forcing in model simulations, are important steps in making comparisons with the proxy record over the last 1000 years.

Climate variability from the decadal over centennial to millennial timescales and transitions from glacial to interglacial are strongly influenced by nonlinear interactions between the changes in solar radiation (due to orbital effects), its absorption in the atmosphere and ocean and the initiation of large ice sheets which influence the quasi-stationary atmospheric waves. These planetary waves are connected with changes in circulation regimes and storm tracks, which act on the ice sheets, by heat and moisture transport. Changes in net precipitation may trigger multiple circulation states in the ocean. Models need to be sufficiently advanced to address these issues.

Coupled GCMs are not yet capable of simulating long-time climate behavior, including transitions from glacial to interglacial conditions, presumably because the full nonlinear feedbacks are not taken into account. To use output from such long model runs to identify internal dynamical variability of the climate system, the model simulations need to be validated.

To compare GCM outputs to proxy data is a difficult issue due to the inherent uncertainties and the ambiguity of the proxies. The signal-to-noise ratio of variability excited by external factors and of internally generated variability needs to be determined.

Millennial and multi-millennial runs with complex GCMs would help to address the extent to which the observed low-frequency variability is related to internal dynamical mechanisms and external forcing changes, such as injection of volcanic aerosols, greenhouse gas concentrations, solar input, land use, vegetation and orography changes. These complex relationships need to be understood within a framework of data and model tools. Data assimilation techniques have been designed to transfer the observational evidence as forcing terms into the evolution equations of a dynamical GCM, to combine proxy data and GCM climate modeling via a nudging of the model's climate toward an observed paleo-climatic state.

In using paleo-data, it is particularly important that the models have similar spatial scales as the data. It is well known that global climate models exhibit most skill at larger spatial scales. This is a significant limitation to the evaluation of paleo-climatic experiments, since most proxy data represent a significantly smaller footprint. To address this problem, regional climate models have been used for dynamical downscaling. Another alternative is statistical downscaling (Reichert et al., 2002). The combined use of models and paleo-proxy data nudging is strongly recommended.

9.7. Issues Requiring Special Attention in Arctic Models

9.7.1. Climate Reanalysis

Available re-analyses such as the ERA40 are of limited value in the Arctic because surface boundary conditions such as SST and sea ice have been prescribed from available data records, which in areas such as the Arctic are imperfect and sometimes inconsistent with the temperature of the atmospheric boundary layer. The same is the case for snow cover, which is model generated during the course of the assimilation and is often different to the observed snow cover. These are serious limitations making available re-analyses less useful in providing consistent data sets suitable for climate applications over longer periods. A dynamical climate re-analysis could be developed (Bengtsson et al., 2006) to overcome such problems.

9.7.2. Arctic Planetary Boundary Layer and Clouds

To improve the reliability of future arctic climate scenarios, improved representations of surface exchange processes between snow, sea-ice and the atmosphere is needed. The Arctic Planetary Boundary Layer (APBL) poses a challenge for GCMs due to its persistent stable stratification and the important role of ice phase microphysical processes in the formation of boundary layer clouds (Dethloff et al., 2001).

The APBL becomes stably stratified when the surface is cooler than the overlying air. The balance between mechanical generation of turbulence and damping by stability varies greatly, creating relatively thin stable boundary layers that range from well-mixed to non-turbulent. The upper sections of the boundary layer can sometimes be decoupled from the surface forcing and properties. The forcing factors of the stable APBL include radiation, conduction, turbulence, subsidence and advection processes, none of which can be neglected. Owing to this complexity the stable APBL is difficult to describe and model (Tjernström et al., 2006).

Often the APBL is associated with a temperature inversion at the surface due to the pronounced cooling of snow and permafrost layers and interaction with the soil. Higher in the stable boundary layer synoptic-scale forcing factors become important and a low-level jet can occur at the top of the stable boundary layer. The humidity exchanges and evaporation and condensation processes (e.g., formation of fog) are also difficult to parameterize. The same still holds for the vertical aerosol structure and its distribution. Different types of turbulence can occur in the APBL.

Under clear sky conditions and in the absence of fog and stratocumulus clouds, turbulence is mainly generated mechanically by wind shears either by friction or topography at the surface or below and above the low-level jet and by gravity waves. These gravity waves are the main contributors to momentum transport in the APBL. Over Greenland strong katabatic winds are not uncommon within the APBL, when cold dense air is accelerated downslope by gravity leading to production of turbulent kinetic energy.

Clouds can form at the bottom of stable boundary layers, which alter the distribution of short and long-wave radiative fluxes and can modulate the dynamics, turbulence and evolution of the APBL. These effects are emerging as important aspects of the climate change issues. Radiation transfer within clouds and between low clouds and the cold surface requires information on the liquid water content, cloud droplet size distribution, cloud cover, aerosol distribution, and surface properties.

Clouds shade the surface and can introduce radiative feedbacks over land as the solar heating at the surface is reduced. Subsidence in a stable APBL can also lead to fog formation in a layer a few meters thin at the surface.

In mixed boundary layers, such as over the open ocean, arctic clouds form at the top of the mixed PBL. They tend to vent moisture from the mixed layer and deposit it into the free atmosphere, changing the diabatic heating distribution. Entrainment through the top of clouds acts as dynamic feedback and can lead to the growth of the mixed PBL with strong vertical heat and momentum fluxes and a strong coupling between the surface and the free atmosphere.

9.7.3. Snow and Surface Processes

The unique properties of snow, such as its high albedo and high latent heat of fusion, have major impacts on interactions between the atmosphere and arctic land surfaces. Snow stores water and nutrients over winter, releasing them rapidly on melt. The ease with which snow can be redistributed by wind and the sensitivity of melt to variations in radiation and temperature with topography lead to snow cover being heterogeneous over many length scales, which is a major challenge for large-scale modeling.

Although sophisticated snow models have been developed for applications such as avalanche forecasting (e.g., Brun et al., 1992; Bartelt and Lehning, 2002), the representations used in NWP and climate models are comparatively crude and retain uncertainties in their parameterizations. Evaluations of these models have mostly been conducted on small scales and for mid-latitude locations for which detailed observations are available (e.g., Essery et al., 1999; Slater et al., 2001; Bowling et al., 2003). These studies have shown large differences in model predictions of snow ablation, particularly for mid-winter melt events that may become more common in a warming Arctic. A major problem for such evaluations is the difficulty in obtaining accurate measurements of solid precipitation (Goodison et al., 1998). On large scales, good estimates of snow extent can be obtained from remote sensing (Frei and Robinson, 1999), but remote measurements of snow mass are less reliable, particularly in mountainous regions and where snow is melting or obscured by vegetation. In comparison with observed snow cover extent on continental scales, seasonal cycles and interannual variability were simulated better by GCMs participating in AMIP2 than AMIP1, but large regional errors remained (Frei and Robinson, 1998; Frei et al., 2003). To validate how well present climate models simulate and predict snow, an inter-comparison project on snow modeling (SNOWMIP) has been initiated.

Wind can transport large amounts of snow, and mass-balance studies have suggested that sublimation of suspended snow can return large amounts of moisture to the atmosphere in dry, windswept arctic environments (Pomeroy and Li, 2000; Déry and Yau, 2001), although few direct measurements of sublimation have been made. Blowing snow processes are not currently represented in NWP and climate models. Although several specific blowing snow models have been developed (e.g., Pomeroy et al., 1993; Gauer, 1998; Liston and Sturm, 1998) they differ widely in their predictions for the climatic significance of sublimation from suspended snow (Xiao, 2000). As sublimation rates are likely to be controlled by entrainment at the top of the suspended layer (Bintanja, 2001), progress on this issues will require linkages to boundary-layer processes.

Vegetation can trap falling and wind-blown snow, influencing snow distributions, and can mask the albedo of underlying snow. Snow held on forest canopies has a large exposed surface area and can be subject to high sublimation rates; snow on the ground beneath a dense canopy is sheltered from turbulence and solar radiation but will receive enhanced long wave radiation from a warm canopy. In addition to sublimation, intercepted snow may be removed from the canopy by unloading or dripping of melt water. Although many models have been developed for forest snow processes (e.g., Yamazaki and Kondo, 1992; Gusev and Nasonova, 2001; Essery et al., 2003), the representations used in NWP and climate models are mostly simple. Interactions between snow and shrubs have received comparatively little study but are likely to attract increasing attention; observations and modeling studies suggest that arctic shrub density can respond to changing climates on decadal timescales (Sturm et al., 2001). Wetlands and lakes are important features of arctic landscapes that are not adequately represented in current models.

9.7.4. Permafrost

Permafrost models driven with climate change scenarios suggest that active layer depths can change rapidly and that permafrost can retreat dramatically over decadal timescales, but model predictions differ appreciably. However, complete thawing of the thick (>10m) layers of permafrost even under sustained warming may take more than a century. On shorter timescales retreat of permafrost should be understood as the disappearance of the frozen ground in near-surface layers and a gradual deepening of the bottom relict permafrost underneath this layer (Anisimov and Fitzharris, 2001). Changes in active layer processes need to be predicted owing to their importance in carbon cycling and impacts on arctic infrastructure. Climate models have only recently begun to include representations of freezing and thawing in their representations of soil thermodynamics (e.g., Cox et al., 1999; Koren et al., 1999). These models only represent shallow layers at the surface (a few meters), so are less suitable for studying long-term impacts on permafrost stability. Poor horizontal resolution presents problems for representing areas of discontinuous permafrost. Snow and vegetation distributions have important influences on permafrost, so improvements in all these features need to be linked.

9.7.5. Arctic Vegetation System

Many models have been developed to predict vegetation distributions from climate data. Some were designed specifically for arctic ecosystems (e.g., Starfield and Chapin, 1996; Kittel et al., 2000), while others were for global application (Cramer et al., 2001). The first applications were to predict equilibrium vegetation distributions for given climate scenarios, but these predictions will be inaccurate if vegetation is out of equilibrium with rapid climate change. Transient simulations were first performed by driving vegetation models off-line with climate model data, a procedure that does not account for the feedback of changing vegetation distributions on climate through changes in surface characteristics and carbon cycling. Impacts on climate were investigated for extreme perturbations, such as removal of all boreal forests (Thomas and. Rowntree, 1992; Douville and Royer, 1997). Recently, a few simulations have been performed with dynamic vegetation models fully coupled to climate models (e.g., Cox et al., 2000).

Simulations are fairly consistent in predicting a northward expansion of boreal forests (Kittel et al., 2000), but differ widely in the rate and extent of this effect. Mechanisms such as dispersal and soil development that will limit the rate of vegetation changes are generally neglected, as are nutrient cycles that are likely to be important for heavily nutrient-limited arctic ecosystems. Although fire is represented in some models, other disturbances such as insect outbreaks, grazing, and land-use changes are ignored.

9.7.6. Arctic Sea Ice

Understanding the seasonal and long-term variability of the arctic climate requires decoding the interactions between the atmosphere, hydrosphere, cryosphere, and biosphere subsystems. One of the major issues in coupled atmosphere-ocean-ice models is the realistic simulation of arctic sea-ice thickness and extent. This is of prime importance because the presence of sea ice greatly modifies the exchange of heat, moisture, and momentum between the atmosphere and the ocean. The atmospheric circulation feeds back due to wind drift on the sea-ice cover. The sea-ice albedo feedback is an important factor in the amplification of climate changes in the Arctic. Therefore, changes in the arctic sea ice may have significant impacts on the arctic and global climate.

Large regions of the North Atlantic Ocean have been growing fresher since the late 1960s as melting glaciers and increased precipitation, both presumably associated with greenhouse warming, have enhanced continental runoff into the arctic and sub-arctic seas. During the late 1960s, a large pulse of freshwater entered the Nordic Seas through Fram Strait and moved rapidly southward along the western boundary in the East Greenland Current. This has been termed the Great Salinity Anomaly (Dickson et al., 1988) and has been widely attributed to the lowest NAO recorded in the past 50 years.

A pronounced dip in the NAO has been associated with a recent spate of freshwater in the coastal Labrador Sea during summer that could have been caused by icebergs moving further south than usual over the past decade. Hakkinen (2003) suggested that the freshening observed over the past ten years is part of a decadal shift similar to the Great Salinity Anomaly. The analysis posits that the freshening is caused by weakened transport of saline waters to the area, evidenced by weak westerly winds that changed oceanic overturning patterns and affected the spread of saltwater to the region.

Climate variations in polar regions arise from the interaction between atmosphere, sea ice, and ocean. To understand and predict this interaction, several numerical modeling experiments have been performed with a hierarchy of coupled and uncoupled sea ice models. These models use various parameterizations of sub-grid processes but improved process models are required to better represent small-scale sea-ice deformation (ridge building), shelf processes, lead and polynya processes (interaction between oceanic and atmospheric boundary layers), open-ocean convection, fluxes between basins, and parameterization of clouds, radiation, precipitation and surface albedo of sea ice for all seasons. For realistic simulations of arctic climate, thermodynamic and dynamic processes connected with sea ice must be taken into account by sophisticated schemes.

The negative radiation balance of the snow or ice surface affects the structure of the APBL over sea ice. This leads to stable stratification in the APBL with a persistent temperature inversion. At the large scale, the downward sensible heat flux prevails and its cooling effect on the APBL is balanced by the advection of warmer air from lower latitudes. Over thick multi-year ice the heat fluxes through the ice and snow are small and the APBL is in local balance with the surface. Over the thin marginal sea-ice zone the APBL is not balanced and must adjust to changing surface properties. These feedbacks with enhanced vertical fluxes of heat and moisture can be very strong over sea-ice free regions.

A major challenge is to develop coupled models of the atmosphere-ocean-ice system in the Arctic and to take into account the two-way feedbacks between the atmosphere and the ocean covered by sea ice of varying thickness and arrive at a proper simulation of the heat, moisture, and momentum fluxes at this thin interface between the stable APBL and the ocean. Deficiencies in the simulation of surface fluxes associated with the model parameterizations may contribute to an unrealistic thermodynamic equilibrium in a coupled model system.

A key uncertainty concerns the sub-grid scale parameterization of sea-ice growth and melt at its base or laterally. Particular attention should be directed to improve models in reproducing anomalous sea-ice conditions. There is a need for sea-ice thickness measurements over the whole Arctic Ocean.

9.7.7. Glaciers

Glaciers are different from sea ice in that they are regions of freshwater ice on land. Their retreat and loss of volume is an indicator of arctic change. (Klok and Oerlemans, 2004; http://www.geo.unizh.ch/wgms/) Glaciers have lost mass over much of the Arctic and sub-Arctic over the past few decades. The especially rapid retreat of Alaskan glaciers represents about half the estimated loss of mass by glaciers worldwide and also represents the largest contribution of glacial melt to rising sea level (ACIA, 2004; Church et al., 2001). Scandinavian glaciers gained mass over the period from the 1960s to the 1990s due to increased precipitation, although their mass balance has become negative in the past few years. The present mass balance of Greenland is negative at low elevations but positive at higher elevations (>1500 m) with an overall increase (Johannessen et al., 2005), and the area covered by summer melt has increased irregularly over the past 20 years.

Glaciers have important influences on regional climate and hydrology, and are expected to be sensitive indicators of climate change. Melting of glaciers also contributes to sea-level rise (Oerlemans et al., 1998). Glacier responses to changing climates are, however, complex integrators of temperature and precipitation changes and differ with geomorphological settings. Improved modeling of glacier mass and energy balances and dynamics is required. As glaciers are typically much smaller than climate model grid scales, downscaling techniques must be developed for driving glacier models with climate model predictions (Reichert et al., 2002) or for coupling models of glacier distributions to climate models.

9.7.8. Arctic Aerosols

Methane and tropospheric ozone are greenhouse gases and have been shown to significantly affect climate. There is clear evidence that tropospheric chemistry plays a significant role in climate change. A major challenge in tropospheric chemistry is to quantify future global methane and ozone radiative forcings on climate. Climate change could in turn have an impact on tropospheric chemistry. Other indirect effects are related to the link between tropospheric chemistry and aerosol formation. Oxidation of several hydrocarbons of natural or anthropogenic origin leads to a significant production of secondary aerosols, which add to the total aerosol load in polluted regions and affect the radiative budget of the atmosphere.

Tropospheric chemistry can also affect the sources and sinks of carbon dioxide and hence the global carbon cycle. For example, there is evidence that acidification and eutrophication affect the terrestrial uptake of carbon dioxide while oxidation of methane, carbon monoxide and other non-methane hydrocarbons lead to a non-negligible carbon dioxide production.

The arctic aerosol cycle exhibits large differences compared to other regions. Summer aerosols are dominated by small particles but in large numbers characteristic of newly formed aerosols (from homogeneous gas phase reactions). Precursor gases for this aerosol formation are not identified but can be either molecules that have been transported over long distances or can be formed from gases such as dimethylsulfide emanating from oceanic leads. Of particular interest is the feedback loop between climate and the formation of planktonically derived dimethylsulfide. Winter aerosols are characterized by low number concentrations of large particles with large mass, which is typical of aged aerosols that have been transported over long distances. These layers of high winter aerosol content are frequently referred to as Arctic Haze (Rinke et al., 2004). The atmospheric aerosol in the Arctic consequently has a summer maximum in number concentration and a winter maximum in mass. The winter meteorology brings into the Arctic pollutants derived from European and Russian sources. Low precipitation amounts combined with the lack of sunlight (thus photochemistry) gives uniquely extensive turnover times for aerosols in the winter Arctic. Isotope studies indicate nominal turnover times of several months. Observations show that during winter the aerosols are distributed in thin layers within the troposphere. The Arctic is also unique in that unlike other oceanic regions the aerosol concentrations are higher aloft than at surface levels. The summer and winter circulations are clearly different with efficient ground level transport into the basin during winter and transport aloft and subsidence within the basin during summer.

Aerosols influence the arctic climate both through direct effects (directly scattering sunlight) and indirect effects (through changing cloud optical properties with changes in cloud droplet spectra). These changes in radiative balance can influence the atmospheric circulation. Furthermore, the aerosols could potential influence snow and ice albedo upon deposition. These influences all contain large uncertainties. The direct effect is probably weak during summer. During the polar night aerosols could be important for reradiating energy towards the surface. The indirect effect of aerosols is one of the largest uncertainties with regard to human-induced climate change. The indirect effect of aerosols on cold (ice) clouds is even more uncertain. Deposition of aerosols onto the surface is at a maximum in spring when the aerosol laden winter air is transformed into clean summer air through precipitation and photochemistry.

Aerosols typically have rapid temporal and large spatial variations with correlation timescales of single hours and correlation length scales of tens to hundred of kilometers. The high variability of arctic aerosols both in concentration and distribution, and their large seasonal differences in behavior and circulation pose great challenges both for observational programs and for modeling efforts. More process studies are required, particularly with regard to the indirect effect of aerosols, to provide useful parameterizations. This will require aircraft and other vertical sampling equipment and needs to be maintained over full seasonal cycles.

The overall modeling issue is the high vertical resolution required to resolve the thin layers that transport aerosols over great distances in the stably stratified winter atmosphere. A recommended strategy is to utilize models to span the temporal and spatial scales between the sparse surface-based observations and remote sensing data. It is recommended that such studies should be pursued within IPY.

The winter arctic aerosols are dominated by long-range transport from western Eurasia. Climate change will influence storm tracks and pathways into the Arctic. A systematic analysis is needed of the range in variability of transport from natural climate variations. At decadal timescales this variability will be large and possibly indistinguishable from shifts in storm tracks.

A problem of particular importance related to aerosols is the continued fate of the air masses when leaving the Arctic. As storms introduce new pulses of aerosol into the region other air masses must be leaving (to satisfy continuity). Upon reaching lower latitudes with sunlight and higher temperatures the aerosols will be exposed to an environment with much shorter aerosol turn-over times, leading to effective deposition of the pollutants in certain regions. The distribution of such areas as well as changes with climate change needs further research.

9.7.9. Climate Chemistry Interactions

Atmospheric chemistry plays a critical role in the perturbation of climate by controlling the magnitudes and distribution of a number of trace gases (Austin et al., 2003). The amount and distribution of water vapor and ozone in the stratosphere critically depend on the atmospheric chemistry, as do the amount of methane and tropospheric ozone.

Direct and indirect effects of anthropogenic aerosols on the climate have the potential to cancel the increased radiative forcing of greenhouse gases since industrialization. A direct effect of aerosols is to scatter and absorb radiation. Stratospheric aerosols greatly alter the atmospheric chemistry in the stratosphere and lead to such changes such as the Antarctic ozone hole, with consequences for climate. The effects of aerosols depend on their chemical composition and mixing state. An indirect effect of aerosols is to interact with clouds (water, ice and cirrus clouds) by acting as Cloud Condensation Nuclei. Although, clouds can also modify aerosols, their optical properties, their size distribution, and their ability to act as Cloud Condensation Nuclei. This indirect effect, which is a strong function of the chemical and physical properties of aerosols, can perturb clouds and even the hydrological cycle.

Changes in climate also affect atmospheric chemistry, and thus atmospheric composition, significantly. For example, a change in water vapor can perturb the oxidation capacity of the atmosphere. The atmosphere is a chemically complex and dynamic system that interacts with the land, oceans, and ecosystems. Most trace gases emitted to the atmosphere are removed by oxidizing chemical reactions involving ozone and the hydroxyl free radical. The rate of this self-cleaning process is often referred to as the oxidation capacity of the atmosphere. Without this process, the present atmospheric composition and climate would be very different.

Changes in stratospheric temperature and water vapor can alter ozone levels. They can for example affect the expected recovery of the ozone layer. A change in temperature or relative humidity can change the chemical and physical properties of aerosols. These interactions and feedback processes are complex and poorly understood. A better understanding of these processes is essential.

9.7.10. Carbon and Methane Cycles

The Arctic plays a key role in global methane budgets. Mixing ratios are highest in the far north, caused by leakage from the world’s biggest gas fields and natural emissions from extensive wetlands. The potential feedback from climate on methane emissions from sub-arctic and arctic wetlands is poorly quantified. Large areas of the Barents, Kara, and Beaufort Seas are underlain by methane hydrate. In places free gas is trapped under hydrate, liable to burst out if the trap decays when water in the shallow sea floors warm by 4 ºC or more. Though small bubbles from disseminated hydrate may be oxidized by methanotrophs, larger outbursts may feed back to global warming.

There is also a risk of major submarine slides on decaying hydrate, as ice melts, similar to the Storegga slide, triggered as Norway deglaciated, that resulted in a 20 m tsunami over Shetland. It is possible that as slides creep before failure, methane emissions may increase. Methane, particularly northern methane, is a major factor in past abrupt climate changes, and better understanding of modern arctic methane should also help in understanding past changes.

Carbon dioxide is absorbed by terrestrial ecosystems and by the oceans. The influence of climate change on the storage and fluxes of carbon to the terrestrial biosphere requires process and case studies to develop earth-integrated system models. The response of the soil carbon reservoir to climate change is poorly quantified and can potentially be a strong feedback mechanism. The interaction between societal responses and climate change must be weighed against the direct climatic responses of ecosystems. Grazing pressure and other human induced changes in land use can have profound effects on landscape and ecosystems. Many models seek depiction of pure climatic response neglecting the parallel process of land-use pressure. These influences must be accounted for in scenario calculations of terrestrial ecosystem responses and consequent greenhouse gas exchange with the atmosphere.

Climate change projections indicate that the arctic basin may be sea-ice free during summer towards the end of the 21st century. The ice-free surface will allow carbon dioxide exchange but the net effect on the global carbon cycle is uncertain. Air-sea exchange is facilitated but there is great uncertainty over the degree of carbon dioxide saturation of surface waters. Combined studies of stratification, freshwater input, nutrient availability as well as marine ecosystem modeling are required to calculate the uptake potential of the ice-free arctic basin.

Carbon dioxide and methane are released to the atmosphere both diffusely from extensive areas and from point sources. These sources may be changing their flux rates slowly in response to gradual climatic shifts or abruptly through threshold shifts in physical or ecological stability. The fluxes are frequently large with respect to atmospheric concentration changes but small with regard to the terrestrial or oceanic inventory, making ground-based inventory studies problematic. Observational programs must span many scales both in space and time.

Earth-integrated system models need better parameterizations of biospheric and soil reservoir responses to climate parameters. Models need to account for land-use pressures in their projections of future states. The Arctic Ocean carbon dioxide net exchange response to diminishing sea-ice cover in the arctic basin requires the integration of oceanic, hydrologic, and ecosystem modeling.

9.7.11. Polar Stratospheric Clouds

An additional aspect of high latitude climate change may be due to optically thick polar stratospheric clouds (PSCs) as a consequence of increased water vapor levels in the stratosphere. Sloan and Pollack (1998) proposed that this mechanism, in combination with increased greenhouse gas concentrations, occurred during the Eocene, when very high surface temperatures existed at high latitudes together with a much reduced pole-equator difference in surface temperature. The addition of PSCs to the polar night stratosphere resulted in a polar wintertime warming of up to 20 °C in a study by Sloan and Pollack (1998). It was proposed that the increased stratospheric water vapor during the Eocene was due to higher fluxes of methane into the stratosphere.

As reported by WCRP/SPARC, recent observations indicate an overall moistening of the stratosphere, and it is has been estimated (Shine et al., ????) that the (global mean) radiative forcing related to this change could be considerable. An overall increase in stratospheric water vapor will favor the evolution of PSCs owing to the increase in specific humidity and the decrease in stratospheric temperatures related to the increased long wave emission.

9.8. Implementation

Many of the proposals in this ICARP II science plan are expected to be implemented under existing programs; including THORPEX (see section 9.2.1) and COPES (see section 9.3). However, special efforts are required for the Arctic in view of the high sensitivity to climate change of sea ice and permafrost, with associated widespread societal and environmental consequences. Observational limitations are a serious concern in the Arctic because of too few in-situ observational platforms and restricted coverage of satellite measurements. It is strongly recommended that additional observing platforms and other observational activities, that are planned for IPY 2007-2009, are considered wherever feasible as part of a future operational system for long-term monitoring and prediction in the Arctic.

The research activities proposed in this ICARP II science plan should preferably be organized in the form of study groups leading to research programs with WCRP-COPES and WCRP-CliC (Climate and Cryosphere Project). The modeling work will require substantial computer resources as very high resolution modeling studies are required. This is because the Arctic is a region with complex geography and one in which critical transport of ocean water masses takes place in narrow passages. Correct treatment of atmospheric, ocean and sea-ice processes is important for accurate prediction at different timescales. Ensemble prediction experiments are also required, putting further demands on computer resources.

As there is a lack of young scientists in this field it is recommended that special dedicated training programs be organized including summer schools for students. More scientists are likely to be required to address the huge amount of data expected from IPY. Funding agencies including the EU research commission should be approached with the objective of putting in place an overarching arctic research plan for the future with advanced modeling as a central tool.

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