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World Climate Research Programme

Report

WCRP Workshop on Seasonal to Multi-Decadal Predictability of Polar Climate

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T.G. Shepherd, J.M. Arblaster, C.M. Bitz, T. Furevik, H. Goosse, V.M. Kattsov, J. Marshall, V. Ryabinin, J.E. Walsh

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Background and purpose of workshop

Over the last few decades, the polar regions have exhibited some of the most striking changes in the observed climate record. Whilst the Arctic has warmed, as expected from the polar amplification of greenhouse-gas (GHG) induced warming arising from the ice-albedo feedback, the observed rate of summertime sea-ice retreat in the Arctic is at the upper limit of climate model predictions. At the same time, Antarctic sea-ice extent is observed to be increasing, contrary to the model predictions. The clearest observed changes in the Antarctic, which are associated with the poleward shift and intensification of the summertime midlatitude jet, are primarily attributed to the ozone hole, which implies that the observed trends will weaken substantially or could even reverse in the coming decades as the ozone hole recovers. However, natural variability in polar regions is large, with substantial power at multi-decadal timescales, and manifests itself in large-scale “modes” whose physical nature and causality are not clear. There are even suggestions of an inter-hemispheric “see-saw”. As a result, it is difficult to determine how much of the recent behaviour might be due to natural variability.

The observed and predicted changes in polar regions have significant implications. In the Arctic, sea-ice changes will directly impact shipping, resource extraction, pollution, and coastal erosion, affecting the lives of inhabitants and those who operate in that region. In the Antarctic, ocean circulation changes will affect the rate of heat and carbon uptake in the Southern Ocean, and could have implications for the stability of the West Antarctic ice shelf. There is, therefore, a pressing societal need to improve the reliability of climate model predictions in polar regions, including both the response to anthropogenic forcings and our understanding of the decadal-timescale variability. The spatial-temporal coherence of this variability offers the hope that some component of it might actually be predictable, given knowledge of the initial state, and the initial state could also be important for the response of the polar regions to anthropogenic forcing. However at this point we do not really know which measurements are most important for constraining that state. In addition to the societal benefits that would result from improved predictions, we would also be in a better position to explain the variability in the evolving climate record.

Because of the strong coupling that exists in polar regions between ocean, sea ice, troposphere and stratosphere, it is necessary for all these scientific communities to work together in order to make significant progress on these problems. This was the motivation behind the WCRP Workshop on Seasonal to Multi-Decadal Predictability of Polar Climate, which brought together approximately 80 experts on polar climate variability and predictability from around the world, representing not only the above-mentioned range of physical disciplines but also observations, theory, processes, and modelling, and with a bi-polar, global perspective[1]. The purpose of the workshop was to summarize the current state of knowledge and identify concrete steps to improve our predictive capability in polar regions. The workshop was hosted by the Bjerknes Centre at the University of Bergen, and was formally opened by the Rector of the University, Sigmund Grønmo. JSC Chair Tony Busalacchi also provided welcoming remarks on behalf of the WCRP.

[1] Copies of the presentations can be found at
http://www.atmosp.physics.utoronto.ca/SPARC/PolarWorkshop/presentations_bergen.htm

Reports on scientific sessions

A preliminary session provided some background context. **Ted Shepherd** presented the scientific motivation for the workshop (as described above), and emphasized the role of the oceans, sea ice, land surface and stratosphere as inherently stable parts of the climate system, with significant inertia, which provide non-trivial boundary conditions (with memory) for the variability that is ultimately driven by the unstable troposphere **(Figure 1)**. This suggests that the key to improved prediction is understanding and accurately representing the sources of memory within the different climate system components, and the feedbacks between them. The stratosphere is a special case because it also represents a source of external forcing (ozone depletion, ozone changes due to solar variability, aerosols due to volcanic eruptions and possibly geoengineering), in addition to GHG forcing. **Ben Kirtman** reviewed recent progress in seasonal to decadal prediction, which lies between the two extremes of weather prediction (dependent entirely on initial conditions, and essentially deterministic) and centennial timescale climate projections (dependent mainly on external forcings). Modern seasonal prediction relies almost entirely on the predictability of ENSO and the skill is generally confined to temperate latitudes. There are believed to be untapped sources of seasonal predictability in the stratosphere, in sea ice, and in the land surface (including snow cover), which are all operative at high latitudes — stratosphere-troposphere coupling is strongest in polar regions — so inclusion of these processes should improve predictive skill at higher latitudes. On decadal timescales, the extratropical ocean is also believed to represent an untapped source of predictability. **George Boer** highlighted the rapidly growing scientific interest in decadal predictability, though noted that the decadal timescale was more of a human than a physical timescale. He reviewed recent studies of predictability in polar regions from a “potential predictability” perspective, which uses a “perfect model” framework to identify what fraction of the year-to-year changes might consist of long-timescale processes (including the forced component) that are potentially predictable given sufficient knowledge of the initial state, as opposed to unpredictable climate noise. These studies hint at some potential predictability in polar regions **(Figure 2)**, but it is not yet clear how large or useful this will be. Some open issues raised by the talks by Kirtman and Boer included the use of a multi-model ensemble (which seems invariably to outperform the “best” models, even for the same ensemble size), how to best combine dynamical and statistical approaches, and how to objectively define the potentially predictable as opposed to noisy part of the signal. In the end, predictability is a property not just of the physical system but also of the filter we apply to it, which depends on the application.

Session 1 was devoted to the mechanisms that rule sea ice variability, the way they are represented in models, and the processes that may help us in providing useful predictions. **Hugues Goosse** discussed the observed and simulated variations over the last centuries. He insisted on the fact that the last 30 years are not necessarily representative of the full range of variability of the system and thus collecting and analyzing longer time series is needed, in particular to evaluate adequately the variability simulated by models. **Ron Kwok** presented a comparison of simulated and observed ice motion and ice transport. He highlighted that many models have strong biases that needs to be reduced in order to improve our ability to make good predictions. **Cecilia Bitz** discussed different mechanisms that could lead to predictability in the system, analyzing ensembles of simulations with a coupled general circulation model (GCM) and observations. Reemergence of anomalies in different seasons related to sea surface temperatures (SSTs) (linked with ice concentration changes) or changes in ice thickness appeared to be particularly promising for predictions of northern hemisphere sea ice area on time scales of a few months **(Figure 3)**. **Jim Overland** proposed a hypothesis in which a reduced summer ice cover would lead to a warmer fall in the Arctic, inducing a decrease in atmospheric geopotential height and a large scale reorganization of the atmospheric circulation that may be characterized by a low index of the Arctic Oscillation. If this mechanism is valid, this would have a strong impact on predictions at seasonal scale as well as on long term changes because of the strong decreasing trend in Arctic ice extent projected for the next decades.

Marilyn Raphael described the sea-ice variability in the Southern Ocean and its links with atmospheric changes. Sea ice is influenced by all the known modes of atmospheric variability in the southern hemisphere: the Southern Hemisphere Annular Mode (SAM), the Pacific Southern America (PSA) pattern, the Semi-Annual Oscillation (SAO), and the Zonal Wave 3 (ZW3). However, none of them explains a lot of the sea ice variance integrated over the whole Southern Ocean, probably because those modes were defined as atmospheric modes, rather than in terms of their impact on sea ice. **François Massonnet** discussed the importance of model physics, resolution and forcing in simulations of Arctic and Antarctic sea ice variability performed with an ocean-sea ice model driven by atmospheric reanalyses. A good forcing was found to be essential. Model physics appeared crucial in order to reproduce well the variability in the Arctic, in particular in summer, while the improvements brought by a more sophisticated model were less clear in the Southern Ocean. In the range of resolutions tested (between 0.5 and 2°), the resolution of the sea ice model was not the most critical issue. **Katharine Giles** discussed the available satellite observations of sea ice thickness and how they could be used to make skillful decadal predictions. Analyzing observed sea ice thickness and concentration, she showed that the summer extent is well correlated with the thickness of the following winter but not with that of the previous winter, suggesting that summer extent could help in estimating the next winter's ice thickness.

Session 2 began with a review by **David Holland** of challenges in understanding and modelling cryospheric processes with an emphasis on ocean ice-shelf interactions relevant to, for example, Greenland glacial fjords and the West Antarctic ice sheet. He emphasized the key role of intrusions of warm deep water in ice-shelf melt. Unfortunately, warm deep water can neither be seen from space nor inferred from gravity. **Karen Heywood** then discussed the physics and observations of Antarctic Bottom Water formation, and the extent to which global climate models are able to capture the large-scale circulation features in the Southern Ocean. She argued that while climate models seem to provide a reasonable representation of the transport of intermediate water, they are much worse at representing the transport of surface and bottom water. Moreover, climate models form deep water incorrectly through open-ocean convection. The next two talks reviewed open ocean processes and the dynamics of the Antarctic Circumpolar Current (ACC). **Sarah Gille** discussed observed recent changes in the hydrographic structure (including ocean heat content) and frontal positions of the ACC **(Figure 4)**, emphasizing that we do not really understand the causality underlying those changes. While studies with non-eddy-permitting ocean models suggest that the shifts in the ACC front have been driven by the changes in the SAM, others have argued that ocean eddies buffer this effect and lead to a very different sensitivity. This is clearly an important issue to resolve in the future. **John Marshall** discussed the central role of the Southern Ocean in the upwelling branch of the global overturning circulation. It is important to understand which parts of this circulation are relaxational (i.e. can accommodate changes elsewhere) and which are 'choke points' that require forcing. In particular, it is not entirely clear the extent to which atmospheric wind stresses and heat fluxes, and winter sea-ice cover, may respond to as well as drive Southern Ocean upwelling.

The focus then shifted to the northern hemisphere. **Andrey Proshutinsky** pointed to the role of the wind driven Beaufort Gyre, alternating between a strong anticyclonic regime accumulating ice and fresh water, and a weaker cyclonic regime releasing the fresh water to the North Atlantic and influencing the overturning circulation. **Cecilie Mauritzen** emphasized the revolution that has occurred in recent years in near real time data acquisition in the Arctic and Sub-Arctic, with more than 30,000 Argo, Ice-Tethered Profiler (ITP), glider, and seal-borne CTD profiles obtained since 2001. The new data will give us the opportunity to narrow down the uncertainties in ocean heat content, fresh water content, and density both for reanalysis and operational products. **Svein Østerhus** reviewed the direct measurements of mass, heat and salt exchanges between the North Atlantic and the Arctic. More than 10 years of measurements show no trends in volume transports, but there has been a rapid increase in heat and salt fluxes. **Tor Eldevik** noted that the exchange of mass, heat and salt over the Greenland-Scotland ridge can be described mathematically by three forced conservation equations. With this approach the sensitivity of the transports to changes in hydrography or forcing can be tested. Climate models that fail to reproduce the three distinct water masses at the ridge will respond differently to forcing perturbations. While oceanic responses to atmospheric forcing are well documented in observations and models, mechanisms for oceanic forcing of the atmosphere outside the tropics are less well understood. **Arnaud Czaja** proposed a new mechanism for ocean-atmosphere coupling in the extra-tropics. While the textbook version is that a warmer ocean surface heats the atmosphere above and creates a baroclinic response, surface temperatures can set the atmospheric lapse rate over the warm western boundary currents and thus communicate the temperature signal throughout the entire troposphere. These moist neutrality situations are currently not parameterized in global atmospheric models, leaving a potential for prediction yet to be fully investigated.

Session 3 examined the role of the stratosphere in predictability. **Paul Kushner** discussed mechanisms for coupling between the stratosphere and the troposphere. He distinguished between direct effects of stratospheric changes on the troposphere, and indirect effects whereby the state of the stratosphere affects teleconnections (e.g. from ENSO) within the troposphere. He also emphasized the impact of model biases, e.g. models with too long annular-mode timescales exhibit overly strong annular-mode responses to external forcings. **Shigeo Yoden** reviewed insights obtained from mechanistic models concerning internal and externally forced variability of the wintertime stratospheric polar vortex, which dominates stratospheric variability. The use of a mechanistic model permits very long simulations (e.g. 15,000 years), which are needed to fully characterize the PDFs of stratospheric variability because of the large amount of decadal variability and high degree of intermittency in Stratospheric Sudden Warmings (SSWs). **Ted Shepherd** reviewed basic aspects of stratospheric variability, and summarized the various physical mechanisms for memory in the stratosphere on both seasonal and interannual time scales, including tropical-polar coupling. Stratospheric models (whether simple or complex) and observations both exhibit strong decadal-timescale variability, but it has yet to be determined how predictable it is.

Judith Perlwitz discussed the impact of the Antarctic ozone hole on the Southern Hemisphere (SH) high-latitude summertime troposphere, which is by far the clearest instance of a stratospheric influence on surface climate, and is a predictable signal since it is associated with stratospheric halogen loading. The surface impact of the ozone hole involves a strengthening and poleward shift of the tropospheric jet (represented by the SH Annular Mode (SAM)), and has implications for the ocean circulation, which are beginning to be studied. The anticipated recovery of stratospheric ozone over the coming decades implies that this component of the recent climate trends will be reversed, with the latest model studies suggesting a near cancellation for summertime trends between the effects of ozone recovery and GHG forcing over the next half century. **Julie Arblaster** discussed the response of the SAM, which controls much of SH climate, to future GHG and ozone forcing, emphasizing that the response to ozone forcing is mostly confined to the summer season. She found that the circulation response to GHG forcing is strongly related to climate sensitivity and arises more from the warming of the tropical upper troposphere, which previous studies have shown induces dynamical (momentum flux) feedbacks through a strengthened subtropical jet, than from polar cooling. **Michael Sigmond** addressed the question of whether the ozone hole might explain the observed increase of Antarctic sea-ice extent. In his coupled model simulations, with a non-eddy-permitting ocean model, the ozone hole led, instead, to a reduced sea-ice extent. This decrease is consistent with a mechanism involving enhanced offshore Ekman sea ice transport arising from the stronger westerlies. A poster by **Cecilia Bitz** also found a decrease in sea-ice extent in response to the ozone hole employing a different model. However, she found that the response was significantly smaller when the ocean model resolution changed from non-eddy-permitting to eddy-permitting, owing to a significant reduction in the poleward heat transport response at higher horizontal resolution. This result is consistent with the 'buffering' effect of eddies that was discussed by Sarah Gille (see above). **Julie Jones** presented a reconstruction of the SAM index over the entire 20th century. This record is important because there is a paucity of long data sets for SH high latitudes. She found that in DJF the recent increase of the SAM index was unprecedented in the historical record, so presumably a response to forcing (which models suggest has mainly come from the ozone hole), whereas in MAM the recent increase was large but still within the range of natural variability **(Figure 5)**. No SAM trends were identified in either JJA or SON.

Session 4 focussed on predictability of the Arctic climate system, and covered ocean-atmosphere exchanges, mid-latitude-Arctic coupling, high-latitude-terrestrial predictability, sensitivities and feedbacks in the Arctic system, and the use of models for prediction. **Xiangdong Zhang** showed how an observational constraint (the sensitivity of Arctic sea ice extent to air temperature) could be used to narrow the range of future sea ice projections obtained from global climate models. Zhang also showed how the recent loss of summer Arctic sea ice is part of a broader Rapid Change Event involving a shift of the atmospheric circulation. **Hiroshi Tanaka** discussed the role of the Arctic Oscillation (AO), which explained about half the Arctic warming from the 1960s to the 1990s. He showed that the AO is almost dynamically orthogonal to the "global warming" component of the recent Arctic change.

Michael Karcher documented the variability of the Atlantic Water inflows and outflows, for which the Arctic Ocean acts as a switchyard **(Figure 6)**. While these inflows have subpolar origins, the Nordic Seas impose their imprint. Karcher showed that North Atlantic inflow anomalies may impact the deep water overflows about 10-15 years after entering the Arctic Ocean, implying some potential predictability of overflow variability. **Koji Shimada** showed that the recent reduction of sea ice in the western Arctic Ocean is due to a combination of three factors: heat, preconditioning, and winds. The inflowing Pacific Summer Water is a source of heat, but its impact on sea ice is amplified by wind-driven changes in the Beaufort Gyre dynamics and the interplay with reduced ice concentrations, Ekman pumping, and topography. **Mark Serreze** discussed the broader issue of polar amplification, and showed that its strongest manifestation in the cold season and the marginal ice zone is indicative of a contribution of a feedback arising from the reduced sea ice. There is a need for coordinated model experiments to assess the impacts of the reduced sea ice extent on the atmospheric circulation elsewhere in the northern hemisphere.

In the first of the "terrestrial" presentations, **David Lawrence** showed that in CCSM3 21st century A1B simulations, the rate of warming over Arctic land areas is enhanced by 1-2°C/decade in autumn and winter during periods of rapid sea ice loss **(Figure 7)**. He showed that the same seasonality and spatial pattern of Arctic land warming was also found in AMIP-type experiments forced by the sea ice loss projected by CCSM3 by the end of the 21st century. Lawrence also showed that 21st century simulations are accompanied by substantial changes of permafrost as defined by the ground temperature at 3 m depth. **Andrew Slater** addressed the simulation of snow and soil temperature within a data assimilation framework. There are severe problems with the available data coverage for these variables, especially in the case of snow water equivalent and depth, despite the potential importance of these variables for predictability on seasonal timescales. Finally, **Hugh Morrison** showed that climate models poorly simulate Arctic clouds, especially the partitioning of condensate into the liquid and ice phases. A key question is whether the frequency of occurrence of different cloud states can be related to certain parameters available at the grid-cell scale. Large-Eddy-Simulation experiments can be exploited for this purpose.

Alex Hall used a suite of CMIP3 simulations to assess the predictable component of Arctic change that is anthropogenically driven. Polar amplification is seen in the surface air temperature, but not in the heat content of the upper ocean, pointing to atmospheric processes as the key to the large spread in the models' polar amplification. The main predictor of a model's response to GHG forcing is the longwave feedback parameter under clear-sky conditions. The models' low-level stratification is closely tied to this feedback, and the models with strong near-surface stratification show relatively little warming because of strong longwave cooling. In general, the models' surface-based inversions are too strong. Hall further showed that the spread in models' rates of sea ice loss is related to two factors: the initial area of thin (<0.5 m) sea ice, and the longwave feedback parameter **(Figure 8)**. **Jens Christensen** raised the issue of potential nonlinearity in the systematic errors of regional climate models, identifying cases where systematic errors in surface temperature had a strong dependence on temperature over particular European regions. Further work is needed to place these dependences into a framework of GHG-induced warming. **Annette Rinke** reported on an ensemble of 15-month hindcast simulations starting in March and September of various years of the 1979-2009 period. The experiments included various combinations of atmospheric, sea ice/SST, and snow initializations. One of the key findings was that certain atmospheric conditions are more predictable than others.

Session 5 consisted of two parts: one on seasonal predictability involving sea ice or snow as predictors, and one on seasonal to decadal predictability involving fully coupled global climate models. **Mark Baldwin** reviewed the evidence for the influence of stratospheric wintertime variability on surface weather regimes. Weak and strong stratospheric vortex events have been shown to influence the frequency distribution of AO/NAO conditions up to 60 days after the events. Unfortunately the seasonal forecast models all underestimate stratospheric variability, indicating that there is still a way to go before the maximum forecast skill from stratospheric effects is realized. **Yvan Orsolini** used the coupled ECWMF seasonal prediction system to show that sea-ice anomalies provide some predictability of Arctic surface air temperature during autumn and early winter **(Figure 9),** consistent with David Lawrence's inferences (see above) using GCM studies, and also that autumn sea ice variability can induce deep temperature anomalies throughout the troposphere and circulation changes influencing East Asia early winter climate. Orsolini also used an atmospheric GCM to show that Eurasian autumn snow cover can influence atmospheric wave trains over the North Pacific and eventually over the North Atlantic. **Judah Cohen** pointed to autumn snow cover over Eurasia as a precursor for stratospheric variability. More snow and a strengthened Siberian High appear to strengthen the Rossby-wave flux into the stratosphere, weakening the polar vortex and thus favouring negative AO situations. Cohen also presented an experimental prediction of the winter 2010/2011 conditions based on his approach. That prediction was then updated and presented to WCRP (Vladimir Ryabinin) on 30 November 2010. As shown by the verification made at the beginning of March 2011 **(Figure 10a)**, the prognosis **(Figure 10b)** turned out to be highly successful and correctly predicted the winter temperature anomaly pattern for the entire extratropical Northern Hemisphere.

In parallel with such observational and reanalysis studies, efforts are being made to improve the ocean/ice assimilation and forecasting systems. Two different methods were presented; one using the Ensemble Kalman Filter approach (**François Counillon**), and a second using a four-dimensional variational approach (**Frank Kauker**). Using data assimilation it is possible to identify key parameters or areas that are particularly sensitive to perturbations, and thus guide process studies or measurement campaigns. In recent years there has been a large increase in studies related to decadal climate forecasts. Three talks were given on this subject, all demonstrating that hindcast experiments do show promising skill both in real and idealized experiments. **Johann Jungclaus** focused on the sources and impacts of variations in the Atlantic meridional overturning circulation. Time scales and mechanisms differ between models, and more work is needed to identify those that work in the real world. **Doug Smith** showed that the North Atlantic also plays an active role through Subpolar Gyre dynamics, with links to tropical convection and hurricane frequency. Of particular interest is the near collapse of the Subpolar Gyre around 1995, seen from altimetry and downstream hydrography, which was discussed by **Ed Hawkins**. The fact that the climate models reproduce this event in forecast mode **(Figure 11)** indicates that the anomalous atmospheric forcing that year (record low NAO after many positive years) played a smaller role than previously believed. **John Walsh** gave the final talk in the session. He showed that model ensembles are generally more skillful in reproducing Arctic climate variations than single models, but only to a certain extent. The skill of the ensembles is reduced if the models with the largest biases are included. In general the models with the best performance also tend to show a stronger sensitivity to greenhouse forcing. Some predictability is expected from low-frequency variability in the Arctic climate.

Synthesis

We understand many of the physical sources of predictability in the polar climate system. For sea ice, memory resides in sea-ice thickness, rather than sea-ice extent, and springtime ice-thickness anomalies can re-emerge in the fall with the summertime memory provided by the ocean. The initial sea-ice thickness distribution is the main control on modelled Arctic sea-ice loss for the first half of the 21st century. For snow, memory resides in snow depth (or snow water equivalent). There is longer-term memory in permafrost, whose disappearance can lead to an albedo feedback through rapid growth of shrubs. For the ocean, SST anomalies have a seasonal memory while longer-term memory resides in the heat and salinity of subsurface water masses, which provide a mechanism for lagged teleconnections. In the Antarctic there is also substantial memory provided by the baroclinic component of the ACC, which exerts a control on the Atlantic Meridional Overturning Circulation. For the atmosphere, there is seasonal memory in the stratosphere, which modulates tropospheric variability, because of the long radiative timescales in the lower stratosphere and the strong seasonal cycle of stratospheric polar variability. There is also longer-term memory in tropical stratospheric winds, manifested in part by the QBO. The Antarctic ozone hole has been the principal driver of summertime trends in SH high-latitude surface climate over the last few decades, which may cease or even reverse as the ozone hole recovers over the coming decades.

Although the field is still in its infancy, early results concerning the extent of polar predictability show promise. . Most of these efforts have taken place in Europe or North America and have therefore focused on the Arctic and North Atlantic. Operational seasonal prediction systems for the Arctic show the impact of summertime sea-ice and fall Eurasian snow-cover anomalies, and September Arctic sea-ice extent appears to be predictable given knowledge of the springtime ice thickness or early to mid summer sea ice extent. Stratospheric Sudden Warmings provide further predictability during winter and spring once they occur, although the extent to which they are themselves predictable is still unclear. On longer timescales, studies of potential predictability within a “perfect model” framework suggest multi-year predictability of the internal variability over the high-latitude oceans in both hemispheres, and the first attempts at decadal prediction have identified the Atlantic subpolar gyre as a key source of predictability, with a teleconnection to tropical Atlantic SSTs.

What we lack is a good understanding of many of the feedbacks between the different components of the climate system. The precise dynamical mechanisms of stratosphere-troposphere coupling remain to be elucidated, although they appear to be well represented in models with sufficiently good climatological mean states. The robust surface responses to stratospheric variability and trends are in surface winds and mean-sea-level pressure gradients, which are dynamically controlled; the surface temperature responses, which are more thermodynamically controlled, are less clear except where they result from advection. The response of Arctic sea ice to surface winds appears to be well understood, but the origin of the overly pole-centric Beaufort Gyre in climate models, which induces significant biases in sea-ice export through the Fram Strait, is not well understood. Although the basic mechanisms of Arctic amplification of GHG-induced warming, which involve feedbacks from sea ice and ocean, are well understood, there are large uncertainties in the magnitude of the surface temperature response arising from uncertainties in the response of Arctic clouds and systematic model biases in boundary-layer stability. While global ocean models generally have a good representation of intermediate-water transport, they have a very poor representation of the transport of surface and bottom water, and incorrectly form deep water by open-ocean convection. This could compromise the realism of the response of the ocean circulation to surface buoyancy forcing. In the SH, the response of the ACC and of poleward ocean heat transport to surface wind trends seems to be very different in eddy-permitting and non-eddy-permitting ocean models, suggesting that the latter may have non-conservative eddy parameterizations that do not correctly “buffer” the ocean response to wind stress forcing.

As a result of all these weaknesses in our knowledge, we do not well understand the physical causality of the large-scale modes of polar variability that are evident in the observed record. This compromises our ability to design appropriate observation, assimilation, and modelling systems for polar prediction, and to explain the observed record.

Unfortunately, we lack many of the key observations needed to constrain the presumed sources of polar predictability; examples include snow depth and snow water equivalent (estimates from passive microwave instruments are widely regarded as useless), sea-ice thickness (estimates from laser altimetry may be acceptable, but they are not now available in real time), polar ocean state estimates including Antarctic warm deep water, and stratospheric tropical winds. An exception is the salinity and heat anomalies entering and exiting the Nordic (GIN) Seas, which appear to be well constrained by hydrographic data in the limited number of communicating channels. However, there has been an explosion of new subsurface ocean observations in the last decade or so from Argo floats and from the recent “seal” network, which are revolutionizing the polar ocean observing system. These observations provide new opportunities for model validation — probably best performed in observation rather than model space, to avoid introducing errors from interpolation, and with a focus on “process-oriented” diagnostics that are not overly sensitive to the time period considered — and offer the potential for vastly improved estimates of the ocean state, a prerequisite for polar predictability. Nevertheless, since the “repeat cycle” for seasonal and especially decadal predictions is rather long, prediction systems will continue to be tested in hindcast mode, for which our poor historical knowledge of the ocean and sea-ice initial states will surely represent a major limitation.

Next Steps

In considering what can be done by the WCRP to make progress in polar predictability, it needs to be borne in mind that it is not the job of the WCRP to coordinate climate science. Nor is there much point in making unsolicited research recommendations. Rather, the WCRP aims to identity those aspects of climate science that benefit from international coordination. That means identifying particular gaps, typically where efforts by individual scientists or groups have run into a wall because of the lack of a wider effort. Since the WCRP has no staff of researchers, high-impact initiatives addressing those gaps need to be developed that can rally the community behind them and attract the support of funding agencies. In order to maintain momentum, these initiatives need to define achievable, tangible deliverables within a broader strategic research plan that is both scientifically exciting and societally relevant. Those deliverables need to leverage existing activities to the extent possible.

There was a clear consensus at the workshop that a notable gap was that between scientific communities, as most people knew only a small minority of the other participants. As discussed above, it seems apparent that progress in polar predictability will require crossing disciplinary boundaries to understand the feedbacks between the troposphere and the stratosphere, ocean, land, and sea ice. In the discussions, it became evident that the nature of these feedbacks appears to be somewhat different in the two hemispheres, because of the different geometries, leading to rather different scientific questions.

In the Arctic, the ocean is contained within a basin with a couple of entry/exit points, and sea ice covers the polar region, allowing a strong ice-albedo feedback. While there are certainly important dynamical processes — e.g. the export of sea ice through the Fram Strait depends on the position and strength of the Beaufort Gyre — climate scientists tend to treat the Arctic primarily from a thermodynamic perspective, focusing on budgets of heat and (in the ocean) salinity. Probably the most burning societal question is the rate of warming in the Arctic, as this has numerous local consequences, including those that relate to an ice-free summertime Arctic. Whilst it is plausible that the most extreme model predictions of summertime sea-ice loss are in fact our best predictions, and that the observed rate of decrease in summertime sea-ice extent is well understood, the confidence we have in those statements needs to be greatly strengthened.

In the Antarctic, the ocean is annular, sea ice is largely seasonal, and the centre of the polar region is covered by land ice and ice shelves. While there are certainly features of interest arising from the longitudinal asymmetry of the Antarctic continent, the dominant climate structures are the circumpolar jets in atmosphere and ocean, and climate scientists tend to treat the Antarctic primarily from a dynamical perspective, focusing on eddy momentum fluxes and jet shifts. Furthermore the largest observed changes in the Antarctic (which occur in summertime) are thought to be associated with the stratospheric ozone hole, reinforcing this dynamical perspective. On the other hand, the basic mechanisms for polar amplification (sea ice-albedo feedback, enhanced atmospheric latent heat flux) also exist in the Antarctic but are being delayed by deep ocean heat uptake, although it is unclear how well climate models represent this delay. Probably the most burning societal question is what is the true response of the ocean circulation to the strengthening and poleward shift of the tropospheric jet, and how will this change in the future as the ozone hole recovers while greenhouse gas concentrations continue to increase, as this has implications for Southern Ocean upwelling and carbon uptake, and possibly for the long-term stability of the West Antarctic ice shelf. In contrast to the situation in the Arctic, there is as yet no plausible explanation for the observed increase in Antarctic sea-ice extent, which remains a major scientific puzzle.

These are, of course, just the current questions, but we can be sure that they will remain “grand challenges” for some years yet, and furthermore that answering them (and comparing and contrasting the behaviour of the two hemispheres) will advance our understanding of the fundamental processes and feedbacks underlying polar predictability. At the same time, a number of general issues and opportunities were identified which apply to both poles:

(i) A better understanding of seasonal predictability, not only for its societal benefits but also for understanding the seasonality of longer-term variability and changes. The WCRP’s Working Group on Seasonal to Interannual Prediction (WGSIP) has the infrastructure to perform prediction studies but needs the expertise of polar scientists to interpret the results of those studies in polar regions and design new experiments.

(ii) A better understanding of decadal variability and its partitioning between internally generated and externally forced components. The WCRP’s Working Group on Coupled Modelling (WGCM) has defined a set of coordinated experiments focusing on the near term (i.e. several decade) time horizon within its CMIP5 activity, which will provide a large archive of model simulations that can be analyzed from this perspective. . In addition to the external forcings identified here, aerosols and solar variability also provide potential sources of decadal predictability. It will furthermore be necessary to improve our knowledge of the nature and extent of past polar climate variability, using proxy information where necessary.

(iii) Improved initial state estimates. Potential improvements in existing observations (or their availability) need to be identified for action by the relevant agencies; coupled assimilation systems including snow and sea ice need to be developed, in collaboration with weather prediction centres who are wrestling with this issue as part of their efforts to improve polar weather prediction; and there needs to be a better understanding of the sensitivity of polar predictability on decadal timescales to initial-state error in the ocean, to guide ocean observational network design.

(iv) A better understanding of potential predictability. The value of a “perfect model” methodology hinges entirely on how realistic the model is. In cases where models have some basic credibility, this approach can be exploited to determine where the predictability lies. In other cases, key model processes that are holding back progress need to be identified for a targeted effort at improvement, either capitalizing on existing activities (e.g. the various GEWEX groups targeting model parameterizations) or stimulating new activities (e.g. modelling of sea ice and ice shelf-ocean interactions). In addition to the model deficiencies identified here, models do a poor job of simulating the radiation budget over the Southern Ocean because of a poor treatment of clouds, and this is likely to be an impediment for studies of polar predictability.

The conclusion of the workshop was that a cross-cutting WCRP initiative was needed in the area of polar predictability, whose first action would be to hold a focused meeting in about six months' time, to develop a detailed implementation plan concerning the above issues. In developing such a plan it will of course be necessary to engage and partner with other relevant research bodies, such as SCAR for the Antarctic and IASC for the Arctic. It was felt that although there were important differences between the Arctic and Antarctic which could lead to differences in priorities, there were also considerable scientific and logistical benefits to be obtained by considering the two poles in parallel, and within the context of global climate. In any case such an approach would emphasize the distinctive contribution of the WCRP. Therefore it was suggested that there should be a single initiative, but with distinct Arctic and Antarctic foci where appropriate. Such an initiative would have to complement existing WCRP activities and exploit potential synergies with the WWRP Polar THORPEX Project.

Acknowledgements

The workshop received substantial financial support from the Norwegian Research Council, and was also sponsored by the Bjerknes Centre, University of Bergen and the City of Bergen. We are extremely grateful to Beatriz Balino of the Bjerknes Centre for coordinating the excellent local arrangements, which made for a very productive meeting.

Figures

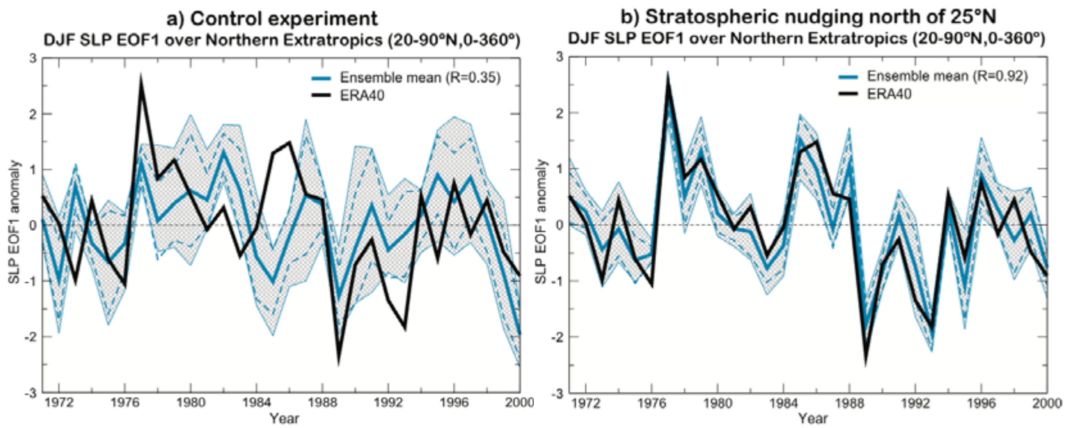

Figure 1. **Evidence for the role of the stratosphere in modulating tropospheric teleconnections.**

A 5-member ensemble of AMIP-type simulations with the Météo-France model (red shading, with the thick red curve the ensemble mean and the dashed lines +/- 1 standard deviation) is not able to reproduce observed (black curve) interannual variations in the DJF surface Northern Hemisphere Annular Mode (NAM) over the 1971-2000 time period, represented here by the principal component of surface pressure north of 20°N, when constrained only by SSTs (left panel), but does so extremely well when the extratropical stratosphere is nudged to ERA-40 reanalyses (right panel). R is the ensemble mean anomaly correlation coefficient with ERA-40. From Douville (2009 GRL).

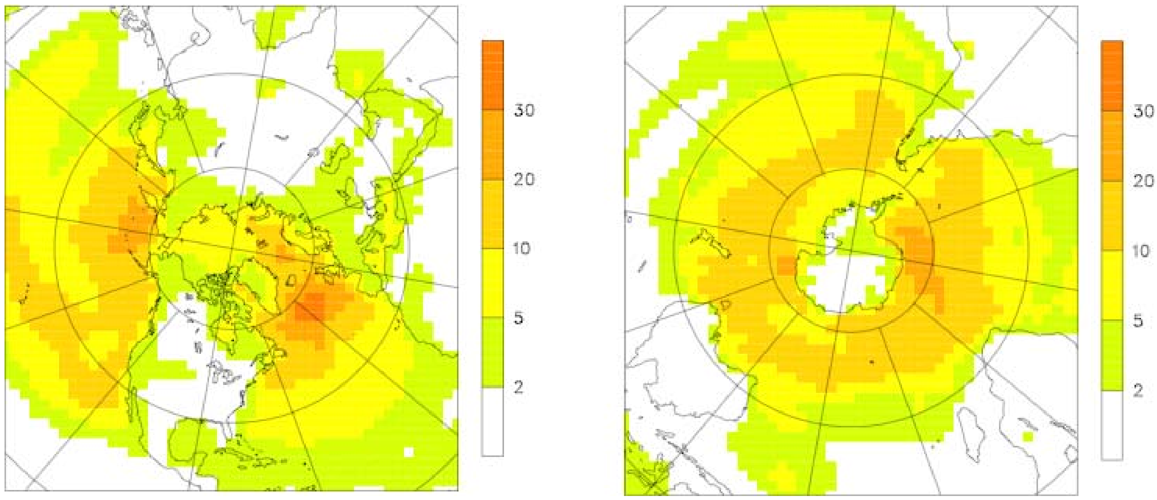

Figure 2. Evidence for decadal predictability of surface temperature at high latitudes from low-frequency internal variability, based on a "perfect model" diagnosis.

The colours show the fraction of the internally generated temperature variance accounted for by decadal and longer timescales within a multi-model ensemble of unforced control simulations in the CMIP3 archive. The presumption is that these long timescales are "potentially predictable" with sufficient information and knowledge (see also Boer and Lambert 2008 GRL).

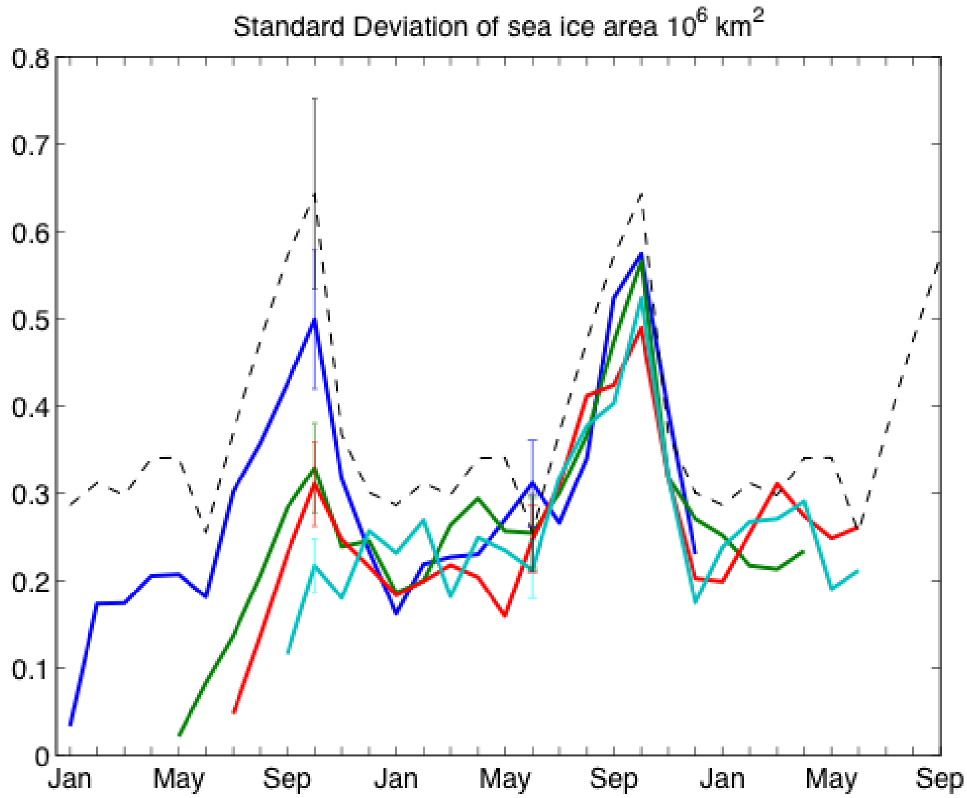

Figure 3. Evidence for seasonal predictability of summertime sea ice based on "perfect model" experiments.

The red, green, blue, and cyan coloured curves in the figure show the growth of the standard deviation of northern hemisphere sea ice area across an ensemble of model simulations where each member was initialized with identical sea ice, ocean, and land surface conditions, starting from different points in the year. The black dashed curve is the saturation level of the standard deviation from a long control run. The coloured curves lie below the black curve, indicating that sea ice area is potentially predictable for up to a year in advance. The initial loss of potential predictability is faster for start dates in the summer season. Nonetheless, based on these experiments, perfect knowledge of the initial conditions in winter only offers modest predictability of sea ice area in the following summer. Figure courtesy of Cecilia M. Bitz, University of Washington.

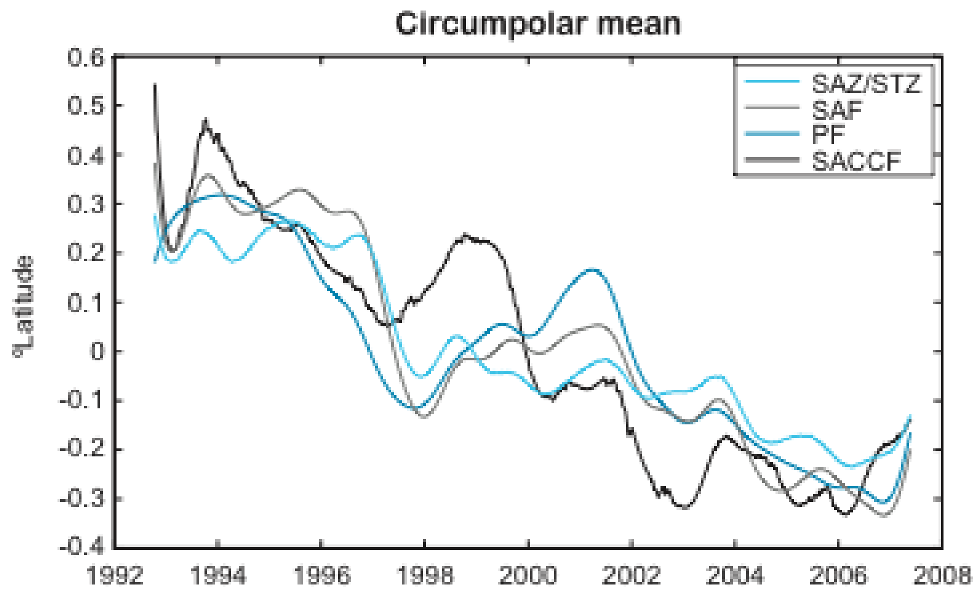

Figure 4. Evidence for decadal predictability in the Southern Ocean from long-term (presumably forced) changes.

The different curves show estimates of changes in the mean latitudinal position of the fronts that comprise the ACC, as inferred from satellite altimeter measurements. (Here, SAZ/STZ is the Sub-Antarctic Zone/Sub-Tropical Zone; SAF is the Sub-Antarctic Front; PF is the Polar Front; and SACCF is the Southern ACC Front.). The ACC has shifted poleward by about 60 km over the last 15 years. From Sokolov & Rintoul (2009 JGR).

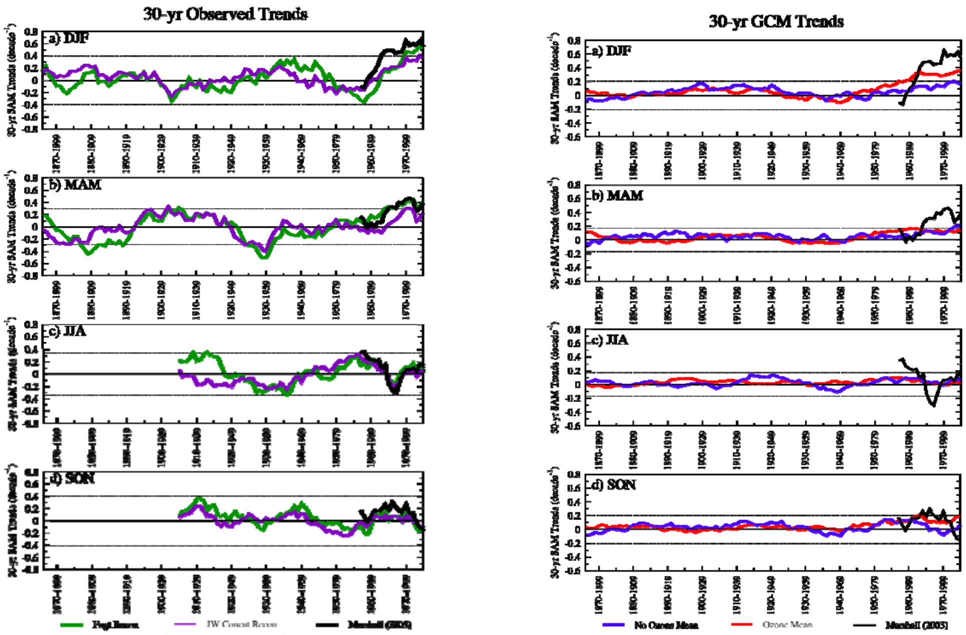

Figure 5. **Evidence for decadal predictability of changes in southern hemisphere summertime atmospheric circulation from ozone depletion and GHG changes.**

30-year trends calculated from reconstructions of the 20th century Southern Hemisphere Annular Mode (SAM) index (left panels) show that the recent summertime trends are unprecedented in the historical record, indicating that they are a response to external forcings. The CMIP3 model simulations (right panels) suggest that the dominant component of the forcing in this season is due to stratospheric ozone depletion. In other seasons, ozone has a negligible impact and the recent trends are just becoming significant in the fall season, but not in the spring, where the simulated trends are too strong. No significant winter trends are evident in reconstructions or simulations. The dotted lines represent the range of internal climate variability from the model's pre-industrial control simulations (left panels), rescaled by the square root of six (the number of non-ozone models) (right panels). From Fogt et al. (2009 J. Clim.).

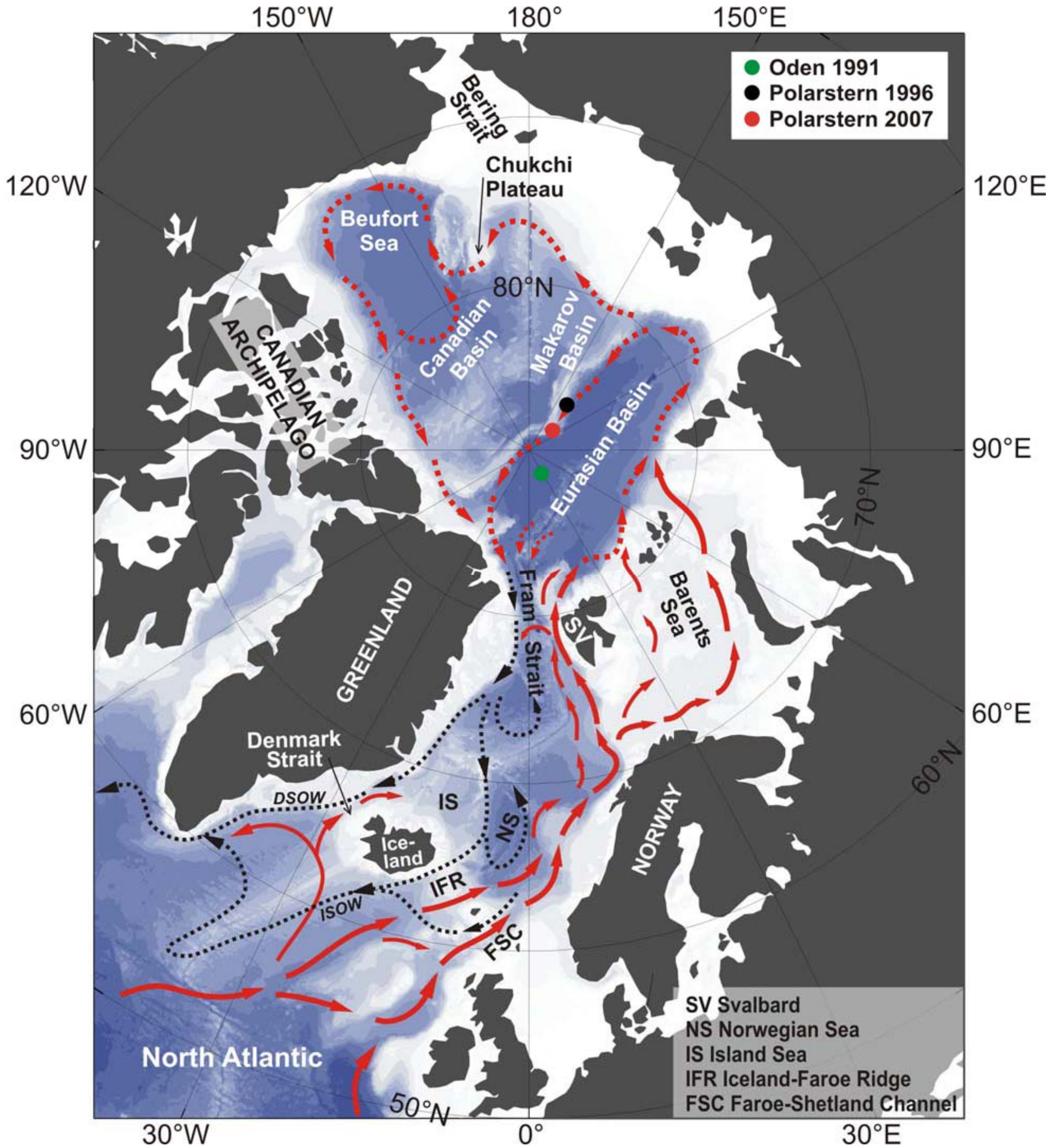

Figure 6. Physical mechanisms of decadal predictability associated with the production of Denmark Strait overflow water (DSOW), which is a major source of North Atlantic deep water.

The North Atlantic inflows come through just two entry points, the Faroe-Shetland Channel (FSC) and the Iceland-Faroe Ridge (IFR), and then are modified by surface fluxes while they transit through the Nordic seas. The Arctic Ocean and Barents Sea act as ‘switchyards’, adding decadal-timescale delays to the system. These delays are variable in time and differ for surface and mid-depth waters. The latter feed the overflows and offer a predictive potential in the form of transient anomalies of the density stratification. For the mid-depth the figure shows a schematic circulation of Atlantic derived water (red solid) and dense, deep water (black dashed). From Karcher et al. (JGR, in revision).

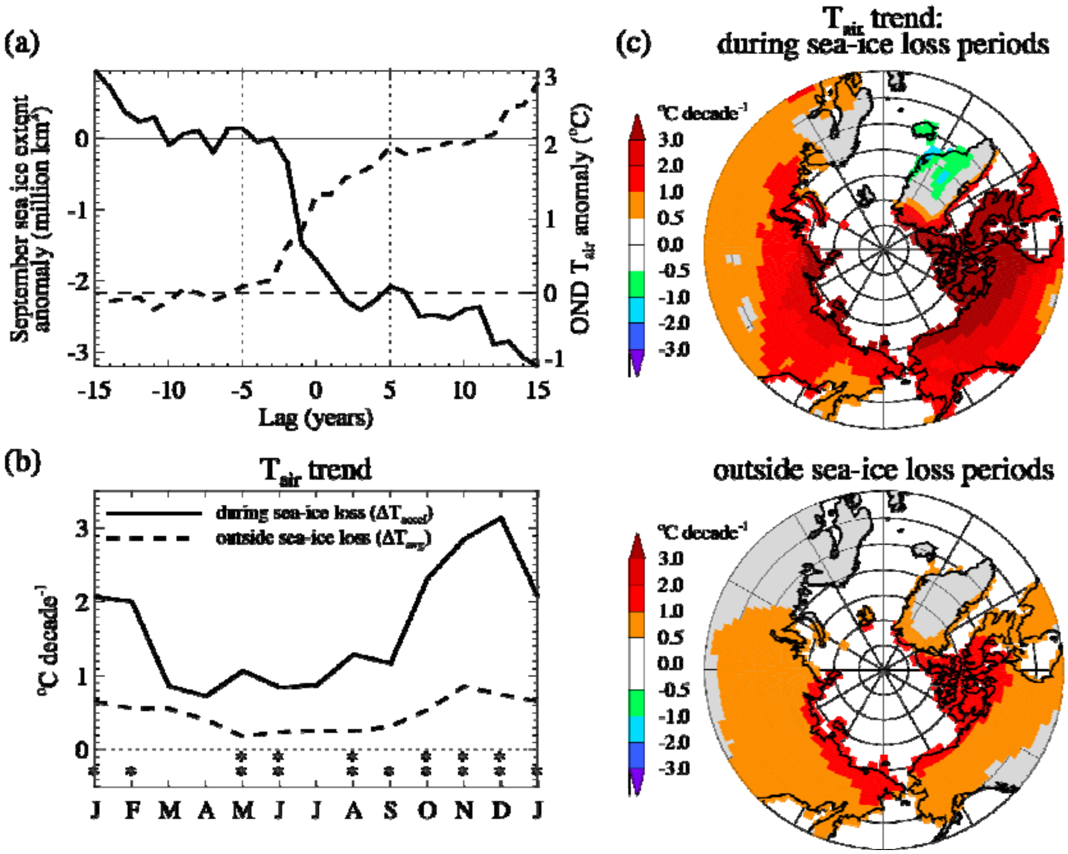

Figure 7. **Evidence for decadal-scale impact of sea ice loss on Arctic land warming rates.**

(a) Composite anomaly time series of September sea ice extent (solid line) and October-November-December (OND) surface air temperature T_{air} (dashed line) over the Arctic land area (within 65–80°N, 60–300°E). Composites are formed by averaging nine 31-year anomaly time series that are centred about the mid-point (lag 0 years) of a rapid sea ice loss event simulated in a CCSM3 21st century A1B simulation. The individual time series are anomalies from the lag -10 to -5 year mean. (b) Average monthly Arctic land T_{air} trends during periods of rapid sea ice loss compared to periods of moderate sea ice loss. The asterisks indicate the months for which the differences in the trends are statistically significant at the 90% (single asterisk) and 95% (double asterisk) levels. The largest impact is found in autumn and winter. (c), (d) Maps of T_{air} trends for OND during periods of rapid and moderate sea ice loss. From Lawrence et al. (2008 GRL).

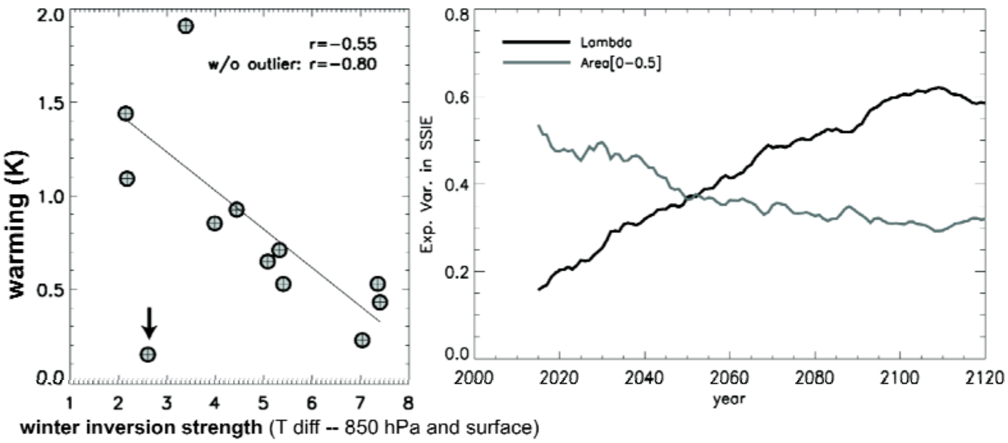

Figure 8. Mechanisms controlling spread in the Arctic climate change predictions of the CMIP3 models.

Left: Relationship between winter inversion strength and annual-mean Arctic warming by the 22nd century (A1B emissions scenario). The stronger the inversion, the more heat is lost by cooling to space (mainly from clear-sky conditions), and the smaller the overall annual-mean warming. The observed inversion strength lies at the left end of the model range, suggesting the models may have unrealistically high levels of negative longwave feedback. Right: Fraction of explained variance in Arctic sea-ice extent changes in CMIP3 models from present day to the indicated year, from the radiative feedback parameter λ (mainly related to inversion strength) (black) and the climatological extent of thin sea ice (grey). These two parameters, which can both be constrained by observations, account for nearly all the predicted changes in sea-ice extent, with the latter dominating in the first few decades and the former dominating later in the century. From Boé et al. (2009 J. Clim.; 2010 Clim. Change Lett.).

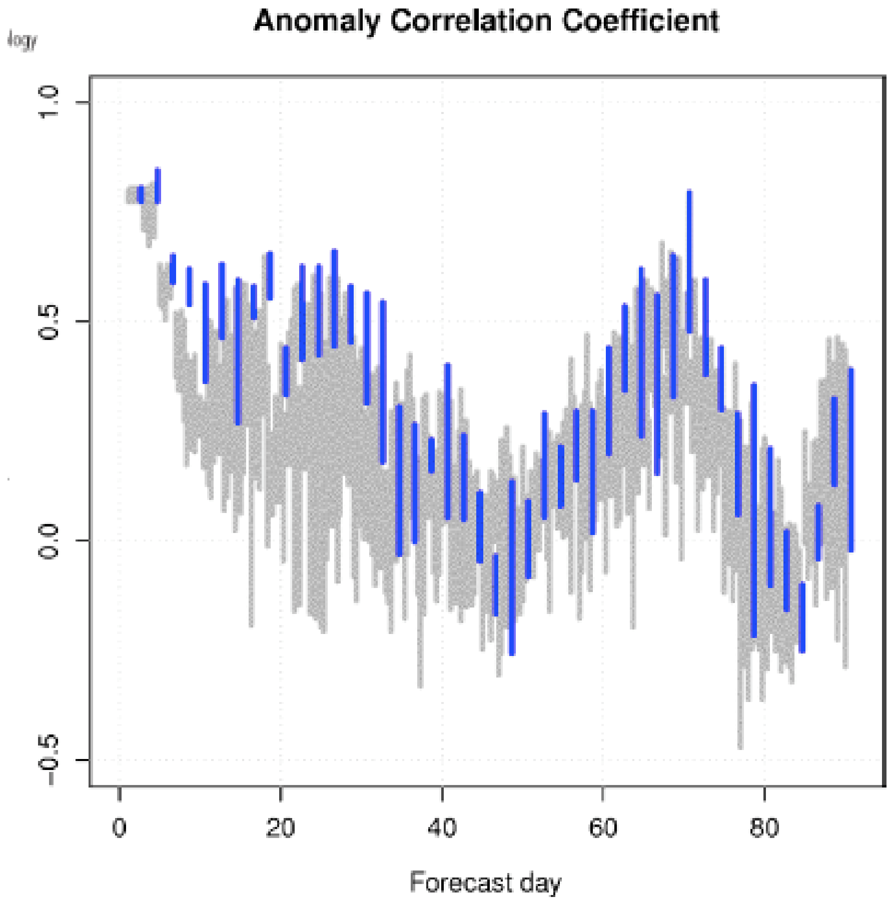

Figure 9. **Evidence for enhanced seasonal predictability of Arctic surface air temperature during fall and early winter 2007 from prescribing sea-ice extent in ensemble hindcasts based on the ECMWF coupled seasonal prediction system.**

Record low summertime sea-ice extent occurred in 2007. The 2-day mean anomaly correlation coefficients are shown as a function of forecast day (starting October 1, 2007), and calculated over high latitudes (60°N-90°N). Each black vertical bar is the envelope of the 5-member hindcasts using the prescribed 2007 sea ice, while the five grey vertical bars on its left are the envelopes of the 5-member hindcasts using prescribed, but "erroneous" or scrambled, sea ice extent from the five preceding years (2002 to 2006). From Orsolini, Senan, Benestad and Melsom, to be submitted.

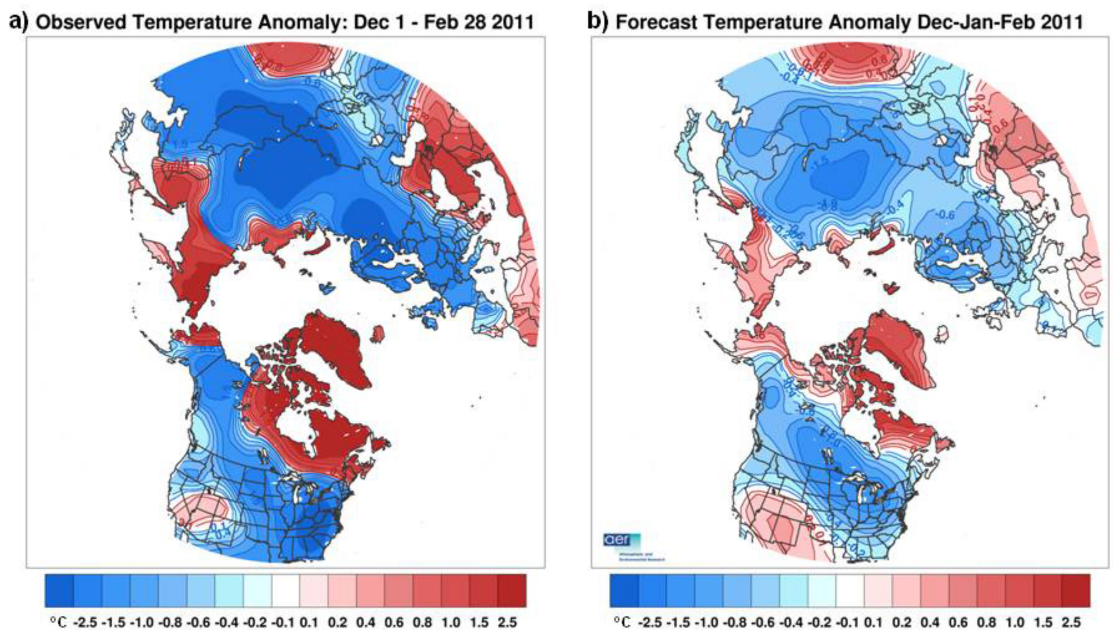

Figure 10. December 2010 - February 2011 seasonal prediction by Atmospheric and Environmental Research.

The accuracy of the seasonal prediction is demonstrated by comparing observed and predicted results. These images show: a) observed and b) predicted winter surface temperature anomalies for the Northern Hemisphere including the North America and Eurasia for December 2010- February 2011. Predicted temperatures were lower than normal for the mid-latitudes and higher than normal toward the Arctic. The model uses October Siberian snow cover and sea level pressure anomalies, as well as sea surface temperature anomalies in the equatorial Pacific in its winter forecast. October 2010 snow cover was observed to be above normal, which favors below normal temperatures for the Eastern US.

See http://www.aer.com/science-research/climate-weather/climate-dynamics/seasonal-weather-forecasts.

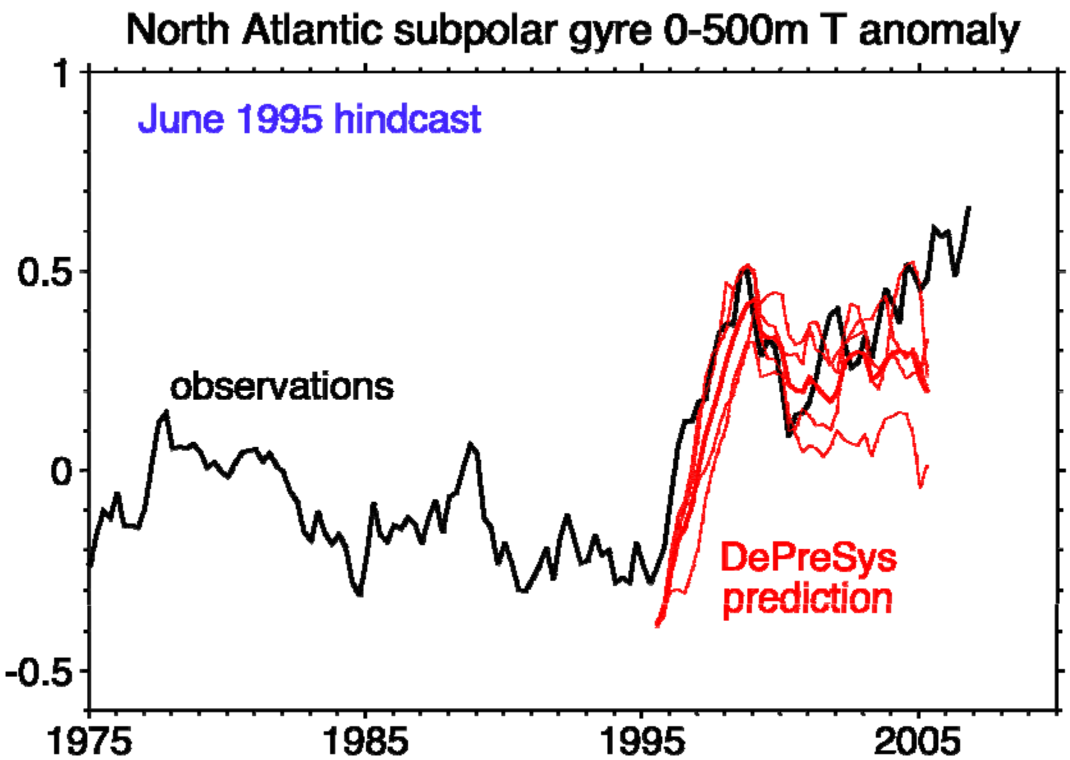

Figure 11. **Evidence for decadal predictability of North Atlantic upper ocean heat content based on the successful prediction of the North Atlantic subpolar gyre warming in 1995/1996 with the DePreSys ensemble prediction system.**

Upper ocean (0-500m) temperature anomalies averaged over the North Atlantic subpolar gyre for a DePreSys hindcast started from June 1995 initial conditions is shown in red, which successfully captures the warming in the observations [black, taken from the Met Office ocean analysis (Smith and Murphy, 2007)]. All temperature anomalies are relative to a 1941-1996 climatology. From PhD thesis of Jon Robson, University of Reading, 2010.

List of Participants

Name	Affiliation
Arblaster, Julie	National Center for Atmospheric Research, USA, and Bureau of Meteorology, Australia
Bakke, Jostein	Bjerknes Centre for Climate Research, Norway
Baldwin, Mark	Northwest Research Associates, USA
Balino, Beatriz	Geophysical Institute, University of Bergen, Norway
Bentsen, Mats	Bjerknes Centre for Climate Research, Norway
Bertino, Laurent	Nansen Environmental and Remote Sensing Center, Norway
Bitz, Cecilia	University of Washington, USA
Boer, George	Canadian Centre for Climate Modelling and Analysis, Canada
Burridge, David	World Meteorological Organization, Switzerland
Busalacchi, Antonio	Earth Science Interdiciplinary Center, University of Maryland, USA
Chen, Linling	Nansen Environmental and Remote Sensing Center, Norway
Christensen, Jens	Danish Meteorological Institute, Denmark
Cohen, Judah	Atmospheric and Environmental Research, Inc. & MIT, USA
Counillon, Francois	NERSC & Mohn-Sverdrup Center for Ocean Studies and Operational Oceanography, Norway
Czaja, Arnaud	Imperial College London, UK
Dethloff, Klaus	Alfred Wegener Institute for Polar and Marine Research, Germany
Drange, Helge	Geophysical Institute, University of Bergen, Norway
Eldevik, Tor	Geophysical Institute, University of Bergen, Norway
Esau, Igor	Nansen Environmental and Remote Sensing Center, Norway
Farahani, Ellie	University of Toronto, Canada
Fer, Ilker	Geophysical Institute, University of Bergen, Norway
Furevik, Tore	Geophysical Institute University of Bergen / Bjerknes Centre for Climate Research, Norway

Giles, Katharine	Centre for Polar Observation and Modelling, Univ. College London, UK
Gille, Sarah	University of California San Diego, USA
Goosse, Hugues	Universite Catholique de Louvain, Belgium
Hall, Alex	Dept of Atmospheric and Oceanic Sciences, UCLA, USA
Haugan, Peter M.	Geophysical Institute, University of Bergen, Norway
Hawkins, Ed	NCAS Climate, University of Reading, UK
Heywood, Karen	University of East Anglia, UK
Holland, David	Center for Atmospheric Ocean Science, New York University, USA
Ivanova, Natalia	Nansen Environmental and Remote Sensing Center, Norway
Jansen, Eystein	Bjerknes Centre for Climate Research, Norway
Jones, Julie	University of Sheffield, UK
Jungclaus, Johann	Max Planck Institute for Meteorology, Germany
Karcher, Michael	Alfred Wegener Institute for Polar and Marine Research, Germany
Kattsov, Vladimir	Voeikov Main Geophysical Observatory, Russia
Kauker, Frank	Alfred Wegener Institute for Polar and Marine Research and OASys GmBh, Germany
Keeley, Sarah	NCAS Climate, University of Reading, UK
Khvorostovsky, Kirill	Nansen Environmental and Remote Sensing Center, Norway
Kindem, Ina	Bergen Municipal Power Company BKK, Norway
Kirtman, Ben	Rosenstiel School of Marien & Atmospheric Science/MPO, USA
Kryjov, Vladimir	Hydrometeorological Research Centre of Russia, UK
Kushner, Paul	Department of Physics, University of Toronto, Canada
Kvamstø, Nils Gunnar	Geophysical Institute, University of Bergen, Norway
Kwok, Ron	NASA/Jet Propulsion Laboratory, California Institute of Technology, USA
Lawrence, David	National Center for Atmospheric Research, USA
Lemke, Peter	Alfred Wegener Institute for Polar and Marine Research, Germany
Magnusson, Linus	ECMWF, UK
Marshall, John	Massachusetts Institute of Technology, USA

Massonnet, Francois	Universite catholique de Louvain, Belgium
Mauritzen, Cecilie	Norwegian Meteorological Institute, Norway
McFarlane, Norm	Canadian Centre for Climate Modelling and Analysis, Canada
Miles, Martin	Bjerknes Centre for Climate Research / ESARC, Norway
Miles, Victoria	Nansen Environmental and Remote Sensing Center, Norway
Morrison, Hugh	National Center for Atmospheric Research, USA
Orsolini, Yvan	Norwegian Institute for Air Research and Bjerknes Centre for Climate Research, Norway
Østerhus, Svein	Bjerknes Centre for Climate Research, Norway
Otterå, Odd-Helge	Bjerknes Centre for Climate Research, Norway
Overland, James	NOAA/Pacific Marine Environmental Laboratory, USA
Paasche, Øyvind	Dept research management, University of Bergen, Norway
Perlwitz, Judith	CIRES, University of Colorado, USA
Proshutinsky, Andrey	Woods Hole Oceanographic Institution, USA
Raphael, Marilyn	Department of Geography, UCLA, USA
Rinke, Annette	Alfred Wegener Institute for Polar and Marine Research, Germany
Rosen, Michelle	SPARC IPO, Canada
Ryabinin, Vladimir	WCRP, Switzerland
Sandø, Anne Britt	Institute of Marine Research, Norway
Schrum, Corinna	Geophysical Institute, University of Bergen, Norway
Serreze, Mark	University of Colorado, USA
Shepherd, Ted	University of Toronto, Canada
Shimada, Koji	Tokyo University of Marine Science and Technology, Japan
Sigmond, Michael	University of Toronto, Canada
Skagseth, Oystein	Institute of Marine Research, Norway
Slater, Andrew	University of Colorado, USA
Smedsrud, Lars	Bjerknes Centre for Climate Research, Norway
Smith, Doug	MetOffice, UK
Sundby, Svein	Institute of Marine Research, Norway

Tanaka, Hiroshi L.	Center for Computational Science, University of Tsukuba, Japan
Tietsche, Steffen	Max Planck Institute for Meteorology, Germany
Villanger, Fredrik	Bergen Municipal Power Company, BKK, Norway
Walsh, John	University of Alaska, Fairbanks, USA
Worby, Anthony	Australian Antarctic Division, Australia
Yoden, Shigeo	Kyoto University, Japan
Zhang, Xiangdong	International Arctic Research Center, USA

Agenda of the Meeting

Monday 25th

8:00	Registration
9:00	Welcome (Sigmund Grønmo, Rector, U Bergen; Tony Busalacchi, Chair, WCRP JSC) Overview of Workshop (Ted Shepherd)
	SESSION 0 CONVENOR AND RAPPORTEUR: TED SHEPHERD
9:30	Ben Kirtman: Seasonal to decadal prediction
10:00	George Boer: Aspects of polar decadal predictability
10:30	Discussion
11:00	*Coffee*
	SESSION 1 CONVENORS: CECILIA BITZ & HUGUES GOOSSE
11:30	Seymour Laxon: Role of ice thickness in Arctic sea-ice predictability
11:50	Ron Kwok: Ice export versus melt in the loss of multi-year sea ice
12:10	Discussion
12:30	Brief Advertisement of Posters
13:00	*Lunch*
14:00	Poster Session *(Sponsored by BKK)*
14:30	Cecilia Bitz: How early can we predict the sea-ice summer minimum?
14:50	Jim Overland: Hot Arctic/cold continents: hemispheric aspects of Arctic change
15:10	Marilyn Raphael: Antarctic climate and sea-ice variability
15:30	Discussion
16:00	*Coffee*
16:30	François Massonnet & Thierry Fichefet: Importance of physics, resolution and forcing in hindcast simulations of Arctic and Antarctic sea ice variability and trends
16:50	Hugues Goosse: Observed and simulated sea ice variations over the last century
17:10	Discussion
17:30	Stock-taking Discussion for Session 1: Led by Cecilia Bitz (Rapporteur: Hugues Goosse)
18:00	End of day

Tuesday 26th

SESSION 2 ***CONVENORS: TORE FUREVIK & JOHN MARSHALL***

9:00	David Holland: Impacts and projections of ice-ocean interaction on sea-level change
9:20	Karen Heywood: Antarctic bottom water formation and variability of Antarctic water masses
9:40	Sarah Gille: Antarctic Circumpolar Current response to the Southern Annular Mode: changes in mixed-layer depth and jet position
10:00	John Marshall: Closing the meridional overturning circulation through Southern Ocean upwelling
10:20	Discussion
11:00	*Coffee*
11:30	Andrey Proshutinsky: Arctic Ocean processes and their predictability
11:50	Cecilie Mauritzen: Changes to ocean hydrography
12:10	Svein Østerhus & Tore Furevik: Poleward propagation of heat anomalies
12:30	Discussion
13:00	*Lunch*
14:00	Arnaud Czaja: A new mechanism of ocean-atmosphere coupling in the extra-tropics
14:20	Tor Eldevik & Helge Drange: On the persistence and possible prediction of the Arctic/Atlantic thermohaline circulation
14:40	Discussion
15:00	Stock-taking Discussion for Session 2: Led by Tore Furevik (Rapporteur: John Marshall)
15:30	*Coffee*

SESSION 3 ***CONVENORS: JULIE ARBLASTER & TED SHEPHERD***

16:00	Paul Kushner: Stratospheric influence on polar climate
16:20	Shigeo Yoden: Numerical studies on internal and external variations of the winter polar vortex with a mechanistic circulation model
16:40	Ted Shepherd: Long-memory processes in the stratosphere
17:00	Discussion (to 17:30)
19:00	*Reception in the historic Håkonshallen, Bergenhus Festning (sponsored by the City of Bergen)*

Wednesday 27th

9:00	Julie Arblaster: Climate signals from anthropogenic and natural external forcings
9:20	Judith Perlwitz: Effect of Antarctic ozone changes on the troposphere
9:40	Michael Sigmond: The ozone hole, the Southern Ocean, and Antarctic sea ice trends
10:00	Julie Jones: Twentieth Century behaviour of the Southern Annular Mode

10:20 Discussion

11:00 Coffee

11:30 Xiangdong Zhang: Recent rapid changes in Arctic climate

11:50 Hiroshi Tanaka: Arctic Oscillation or ice-albedo feedback: A discrepancy in the warming pattern of the IPCC model projections

12:10 Discussion

12:30 Stock-taking Discussion for Session 3: Led by Ted Shepherd
(Rapporteur: Julie Arblaster)

13:00 Lunch

SESSION 4 CONVENORS: VLADIMIR KATTSOV & JOHN WALSH

14:00 Michael Karcher: On the connection of Atlantic inflow variability and the overflows via the Arctic Ocean loop

14:20 Koji Shimada: Influence of activations of sea ice motion and upper ocean circulation on recent Arctic climate change

14:40 Mark Serreze: Predictability of the Arctic air temperature field

15:00 Discussion

15:30 Coffee

16:00 David Lawrence: The terrestrial response to, and role in, Arctic climate and climate change

16:20 Hugh Morrison: Buffering and self-organization of the Arctic cloud-atmospheric boundary layer-surface system

16:40 Andrew Slater: Land data assimilation for seasonal prediction and beyond

17:00 Discussion (to 17:30)

19:00 Workshop Dinner (sponsored by the Bjerknes Centre and the University of Bergen)

Thursday 28th

9:00 Alex Hall: A strategy to improve projections of Arctic climate change

9:20 Jens Christensen: Arctic climate system modelling: on the role of systematic errors

9:40 Annette Rinke & Klaus Dethloff: The role of regional Arctic processes for predictability on seasonal to inter-annual time scales

10:00 Discussion

10:30 Stock-taking Discussion for Session 4: Led by John Walsh
(Rapporteur: Vladimir Kattsov)

11:00 Coffee

SESSION 5 ***CONVENORS: TORE FUREVIK & VLADIMIR RYABININ***

11:30	Mark Baldwin: Stratospheric impact on seasonal prediction
11:50	Yvan Orsolini: Seasonal predictability over the Arctic: exploring the role of boundary conditions
12:10	Judah Cohen: Impact of snow cover on seasonal prediction
12:30	Discussion
13:00	*Lunch*
14:00	Laurent Bertino & Francois Counillon: Ocean assimilation and forecasting
14:20	Frank Kauker: Seasonal ice forecasting and variational data assimilation with the coupled sea ice-ocean model NAOSIM
14:40	Johann Jungclaus: Decadal climate predictions: the North Atlantic and Nordic Seas
15:00	Doug Smith: Decadal prediction of the North Atlantic sub-polar gyre and associated climate
15:20	Discussion
16:00	*Coffee*
16:30	Ed Hawkins: Decadal predictability of the Arctic and Atlantic
16:50	John Walsh: A probabilistic framework for prediction of Arctic change
17:10	Discussion
17:30	Stock-taking Discussion for Session 5: Led by Vladimir Ryabinin (Rapporteur: Tore Furevik)
18:00	End of day

Friday 29th

SESSION 6 ***CONVENOR: TED SHEPHERD***

9:00	Rapporteurs' Reports and Discussion: Shepherd, Goosse, Marshall
10:20	*Coffee*
10:50	Rapporteurs' Reports and Discussion: Arblaster, Kattsov, Furevik
12:30	*Lunch*
14:00	Road Map Discussion: Led by Cecilia Bitz & John Walsh
15:30	*Coffee*
16:00	Discussion, continued
17:00	End of workshop

Posters

NR	AUTHOR	TITLE
1.	Laurent **Bertino**	TOPAZ: the MyOcean Arctic forecasting system
2.	Cecilia **Bitz** & Clark **Kirkman**	Climate Response to Ozone Trends in an Eddy-Resolving Ocean Climate Model
3.	Lin-Ling **Chen**	Accumulation over the Greenland Ice Sheet represented in reanalysis data and related atmospheric circulation
4.	Igor **Esau**	The planetary boundary layer feedbacks in polar latitudes
5.	Ed **Hawkins**	The potential to narrow uncertainty in regional climate predictions
6.	Natalia **Ivanova**	Arctic sea ice variability observed by satellite passive microwave sensors: A comparison of sea ice algorithms
7.	Kirill **Khvorostovsky**	Decadal elevation changes of the Greenland ice sheet
8.	Vladimir **Kryjov**	DJF 09/10, a winter of extremely low Northern Hemisphere Annular Mode: Was it predictable?
9.	Victoria **Miles**	Helheim outlet glacier interaction with the Sermilik Fjord on the East Greenland Coast
10.	Yvan **Orsolini**	Cooling of the wintertime Arctic stratosphere induced by the Western Pacific teleconnection pattern
11.	Svein **Østerhus** & Tor **Gammelsrød**	Bipolar Atlantic Thermohaline Circulation (IPY-BIAC)
12.	Steffen **Tietsche**	Towards sea-ice initialization in coupled climate models