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WWRP/PPP No. 1 - 2013

WWRP Polar Prediction Project Science Plan

WWRP World Weather Research Programme

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WORLD METEOROLOGICAL ORGANIZATION

WORLD WEATHER RESEARCH PROGRAMME

WWRP/PPP No. 1

WWRP Polar Prediction Project

Science Plan

APRIL 2013

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INTRODUCTION

This document provides background on the science issues for the WWRP Polar Prediction Project (WWRP/PPP). The WWRP/PPP Implementation Plan, as the second publication in the WWRP/PPP series (WWRP/PPP No. 2 – 2013) should be seen as the definitive document for this project.

The eight sections cover the science issues and challenges for each of the eight research goals for the WWRP/PPP:

1) Improve the understanding of the requirements for, and evaluate the benefits of, enhanced prediction information and services in polar regions
2) Establish and apply verification methods appropriate for polar regions
3) Provide guidance on optimizing polar observing systems, and coordinate additional observations to support modelling and verification
4) Improve representation of key processes in models of the polar atmosphere, land, ocean and cryosphere
5) Develop data assimilation systems that account for the unique characteristics of polar regions
6) Develop and exploit ensemble prediction systems with appropriate representation of initial condition and model uncertainty for polar regions
7) Determine predictability and identify key sources of forecast errors in polar regions
8) Improve knowledge of two-way linkages between polar and lower latitudes, and their implications for global prediction.

1. USER APPLICATIONS AND SOCIETAL BENEFIT

The primary goal of the Polar Prediction Project (PPP) is to advance scientific knowledge such that society, both within and outside of polar regions, may benefit through applications of better information and improved services. While realizing this goal depends upon achieving an improved understanding, characterization and modelling of atmospheric, oceanic, and land surface processes, the PPP acknowledges the parallel challenge of translating scientific success into societal value. Meeting this challenge demands the application of social science to better understand weather-related decision-making and communication processes that underpin value-generating actions, and to improve methods to evaluate impact and measure social and economic value across a wide spectrum of potential user communities and cultural, social, political, economic and geographic contexts.

1.1 Background

While there is a dearth of social scientific research that explicitly treats the use and value of weather information in polar regions, established programmes of study examining adaptation to anthropogenic climate change (e.g., ArcticNet, some IPY projects) offer potential opportunities for collaboration on research at the temporal scale of weather-related hazards. In exploring the vulnerability and resilience of people, activities and interests to the impacts of climatic change, such studies1 often make reference to weather-related phenomena. Moreover, this research has identified several unique pressures that contribute to the rationale for making the polar regions a target for the application of improved weather prediction science and services and point to several benefit areas — ideas that are also reflected in recent work by the World Meteorological Organization (WMO) Executive Council Working Group on Polar Observations, Research and Services (EC-PORS) Task Team (*Damski et al. 2012*).

The polar regions represent one of the last major geographic frontiers of natural resource discovery and development on the planet. Technological and engineering advances over the past 40 years, especially in the areas of telecommunications, transportation, and industrial processes, coupled with escalating global market demands for raw materials like oil, natural gas, and minerals, have drawn considerable investment, research and development, migration (in some areas), and political interest to the polar territories. The latter is partly a function of the natural resource wealth and implications for security or sovereignty, but it also stems from growing attention and concern for indigenous societies and northern communities whose traditional lifestyles, livelihoods and cultures have been dramatically influenced over the past five generations through exposure to non-indigenous values, social and economic development policies, and transboundary environmental issues (e.g., transport and deposition of toxic air pollutants, stratospheric ozone depletion, climate change).

As shown in Figure 1, indigenous peoples now represent a small fraction of the total northern polar population. Accompanying demographic shifts, the past century has also witnessed significant changes to the physical and biological environment encompassing both poles, for example in the Arctic where substantive atmospheric and oceanic warming with commensurate reductions in sea ice extent and thickness and adjustments in the composition and health of endemic species and ecosystems (Arctic Climate Impact Assessment, 2004).

This context of development pressure coupled with significant socio-cultural, technological and environmental change, translates into a great potential demand for weather prediction and related services — essentially one may argue that 'more' is becoming exposed to weather-related hazards, and that which is exposed may become more sensitive to weather and thus have greater need for weather information.

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[1] *For syntheses see: Arctic Climate Impact Assessment, 2004; Ford et al. 2012; Team and Manderson, 2011*

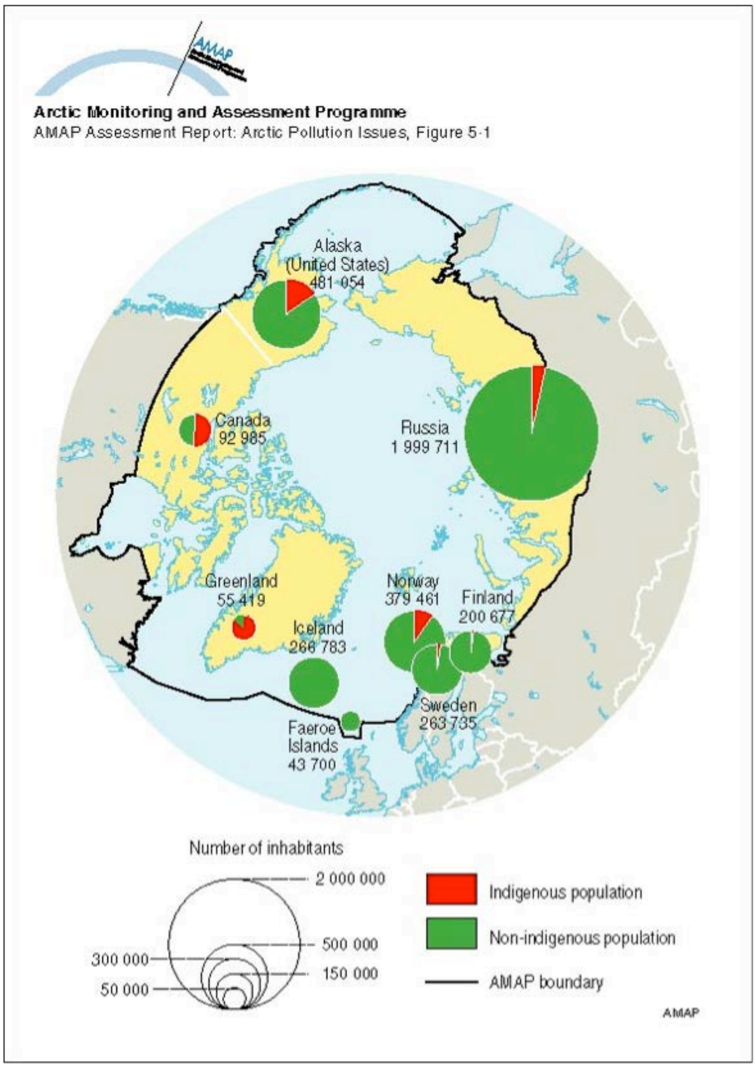

Figure 1 - Distribution of Arctic indigenous and non-indigenous population by nation (AMAP, 1998; Figure 5.1)

Growth in resource development, transportation, tourism[2], and other industries and services means that more people, economic activity, and infrastructure may become exposed to conditions that affect safety, health, mobility, and productivity. In part this growth is stimulated by realized or expected changes in climate; for example, recent variation in sea ice cover and anticipation of a tripling of the duration of the Northern Sea Route season by the 2080s (Arctic Climate Impact Assessment, 2004). Over one million passengers are now carried by cruise ships through polar waters each year, with non-traditional destinations (Antarctica, Arctic Canada, Svalbard, Greenland) growing in popularity (*Eijgelaar et al. 2010*). The inability to retrofit or upgrade Arctic cruise vessels to current ice standards (*Brosnan 2010*) is a concern that translates into even greater need for accurate environmental predictions to aid navigation. Polar great circle routes are now used routinely for thousands of intercontinental commercial and cargo flights (U.S. National Research Council 2008), and resource development activities are placing increasing demands on existing winter road infrastructure and are encouraging the development of all-season highways in the Canadian arctic (*Andrey et al. 2004*). With expanding activity comes greater demand for services such as emergency search and rescue, ice-breaking, and navigation support (International Ice Charting Working Group 2007 - and, by extension, increased need for high quality environmental prediction services.

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[2] *An excellent review of Antarctic and Arctic/sub-Arctic tourism is provided by Hall and Saarinen (2010)*

Recognition of the important role that polar regions occupy within global environmental systems, including climate, has placed increasing demands for scientific investigation, semi- and permanent research stations, and various forms of in-situ and remote environmental monitoring, with corresponding needs for weather information in support of tactical decision-making (e.g., Antarctica, *Bromwich et al. 2005*; various International Polar Year projects). For example, aircraft departing from New Zealand support a wide range of research activities in the Antarctic but are sensitive to forecasts of fog, low cloud, and poor visibility at the Antarctic landing site (McMurdo Station) for which there are no alternates. One useful metric of impact is the number of flights leaving New Zealand but having to turn around once they reach the point of safe return because of an unpredicted deterioration in the weather at McMurdo Station. A typical cost for such turn-arounds is $US100,000 per occurrence and the frequency of these events has been steadily decreasing since the Antarctic Mesoscale Prediction System (AMPS; http://www.mmm.ucar.edu/rt/amps/) effort was started in 2000.

Accompanying the increase in exposure is evidence of greater sensitivity to weather. For instance, cultural tools and traditional knowledge used by members of certain indigenous societies in the Arctic to deal with weather-related sensitivities and hazards are failing in some situations. Social scientists have documented the inconsistency between expectations based on traditional knowledge, for instance when sea ice will support travel or where caribou or other country foods should be available, and what is being actually experienced (e.g., *Prno et al. 2011; Furberg et al. 2011*). This erosion of the efficacy of natural knowledge may offer an opportunity to incorporate (i.e., complement but not replace) enhanced scientific prediction (*Pennesi et al. 2012*). In addition, the influx of people and industries into polar regions from lower latitudes may be accompanied by inadequate experience with polar weather and environmental conditions — itself a possible source of increased sensitivity. As the climate changes, infrastructure and related systems (e.g., airports, roads, housing and other buildings) designed to be resilient under past conditions and assumptions concerning, for example, permafrost depths, coastal erosion, avalanche risk, and snow density/loads, may prematurely deteriorate or fail (Arctic Climate Impact Assessment 2004; *Andrey et al. 2004*). These emerging sensitivities may place an even greater emphasis on short-term prediction to ameliorate impacts until more suitable design criteria become incorporated in the normal life cycle replacement of infrastructure.

1.2 Benefit Areas

The previous discussion identified several pressures making the polar regions a target for the application of improved weather prediction science and services and pointing to several preliminary benefit areas. These are outlined in Figure 2 and broken into primary categories that align to interests within the polar regions (Regional), outside of polar regions (Extra-Regional), and a combination of the two. It will be necessary to populate the details behind each beneficial use area — the decision problems and issues and the characteristics of the decision makers and decision making environment — before substantive social scientific analysis is undertaken through the PPP.

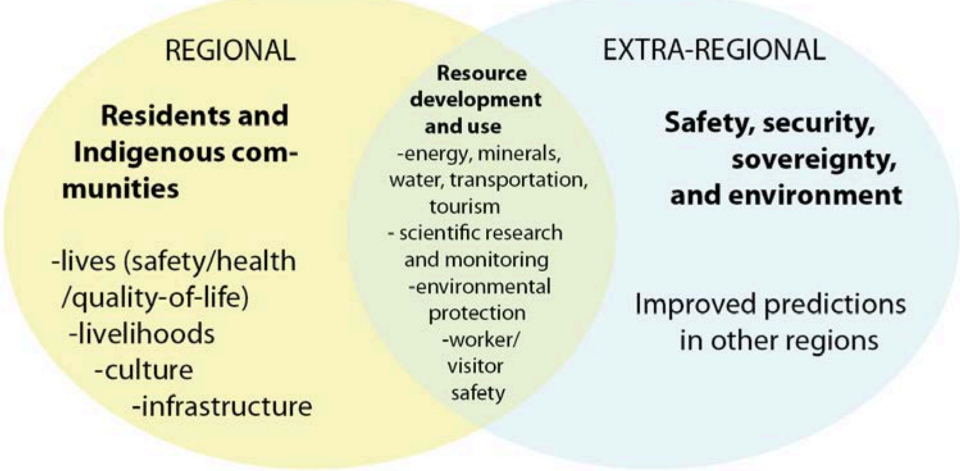

Figure 2 - Potential benefit areas for the application of improved weather-related predictions

One noteworthy area that will add significant complexity to any future PPP evaluation is the assessment of benefits of improved polar prediction capabilities that reach beyond the Arctic and Antarctic, and on time scales well beyond a few days. Some high-impact weather in the mid-latitudes is ultimately linked to environmental conditions in the polar regions. For example, westerly or easterly flow across the southern tip of Greenland leads to the generation of so-called Greenland tip jet events, which cover substantial areas of the northern North Atlantic making this region one of the windiest oceanic areas anywhere on the globe. Furthermore, polar lows - besides their impacts in the Arctic - frequently penetrate well into the mid-latitudes severely affecting countries such as the UK, Netherlands and Germany. There is also an increasing amount of evidence suggesting that loss of Arctic sea ice increases the amplitude and persistence of large-amplitude planetary waves over the whole of the Northern Hemisphere (*Francis and Vavrus 2012; Overland et al. 2012*), which may explain, for example, the frequent occurrence of relatively cold recent winters in Central Europe. Improved representation of key polar processes in models, for example, is expected to feed into climate models, thereby leading to reduced uncertainties of regional climate change projections. Moreover, improvements of polar aspects of data assimilation systems will eventually find their way into future reanalyses. This along with improved conventional and satellite observing systems will enhance our monitoring capabilities of the climate system. Understanding and estimating the social and economic value of teleconnections from polar to non-polar regions and from weather to climatic temporal scales is an important component of overall benefits and needs to be addressed.

1.3 Knowledge Gaps and Important Areas for Social Scientific Inquiry

Despite the lack of substantive polar-specific research on the communication, use and value of weather information, a substantive literature exists that treats non-polar applications. This research draws from a variety of social science disciplines that have as a central theme the explanation of human behaviour, including economics, sociology, psychology, anthropology, political science, human geography, and communication studies. Applied to the polar prediction theme, these areas of expertise could inform how individuals, groups and organizations seek, obtain, perceive, share, comprehend, use and value weather and related risk information in making decisions. In particular, it is important to understand how changes in the attributes of the information and knowledge - for example accuracy, precision, or the manner in which it is communicated, and the characteristics and situational context of the user, who might be a weather forecaster, resident of an Inuit community, or mineral exploration engineer - affect decision-making processes, associated behaviours, and particular outcomes of interest (e.g., safety, health, prosperity, etc.).

The methodological domain of social science encompasses both qualitative and quantitative approaches. Ethnographic field research, whereby the subject participants are observed in their natural settings or through direct interaction with researchers, is an example of the former (e.g., examination of social constructions of a severe weather event in northern Canada; *Spinney and Pennesi 2012*). A statistical analysis of questionnaire survey data is representative of the latter (e.g., tourist perceptions of weather in Scandinavia; *Denstadli et al. 2011*).

Blending results from studies adopting qualitative and quantitative approaches will be necessary but difficult for this project (given respective roots in interpretive/critical and positivistic perspectives). The extent to which even quantitative study findings can be aggregated and generalized across polar regions is questionable and a targeted series of independent case studies, demonstrations or applications may be a more achievable objective. Given the sparse population of the Arctic and limited activity in the Antarctic, the availability of large secondary social and economic data sets directly relevant to the use of polar weather forecast information is likely very limited. It will be necessary to invest in original research and data collection, though it may be possible to borrow from recent studies and projects that have examined adjustments to current and potential climate change impacts.

Given this backdrop and the present state of understanding in polar regions, three lines of inquiry are proposed below to advance our understanding of user application and societal benefits:

Estimation and analysis of historic and current use

Somewhat rudimentary, but essential to further deeper inquiry, is the assemblage of basic knowledge about the extent and efficacy of existing polar prediction forecasting across the various benefit areas. It is near impossible to evaluate the benefits of a new system, model, product, or service to society without establishing a baseline from which to develop comparisons. Who is making use of current products and services; how were the products conceived, developed, and tested; and how has the use of this information influenced decision-making and to what end or benefit?

The EC-PORS Services Task Team has made some progress by developing a survey component to assess the needs and perspectives of users/customers on weather, water, and climate products in the high latitude regions (*Damski et al. 2012*). It was added to an existing instrument employed in a European Commission Framework project (Sea Ice Downstream Services for Arctic and Antarctic Users and Stakeholders (SIDARUS)). It provides an element of a high level scan and could serve as a platform from which to tackle deeper questions with particular users within priority benefit areas.

Communication of risk, opportunity and uncertainty across user types

One of the deeper questions is to understand how the nature of the message content (e.g., raw meteorological element, impact expectations, suggested actions; explicit uncertainty; precision; use of analogues and societally-relevant verification measures), media (e.g., conversation, Internet, mobile device, video, radio, print, etc.), format (e.g., text, numeric, narrative; audio, visual), frequency, timing, and source (e.g., trust, credibility factors), in relation to the decision problem(s), interacts with situational variables (e.g., institutional, technical, political, social, cultural, and economic factors) to influence individual and collective perception, attitudes and decision-making behaviour? How do these relationships and preferences vary over time, across individuals within a use sector/benefit area, by region and, especially significant in the Arctic, between people typically reliant on traditional versus scientific knowledge?

Methods to evaluate and integrate 'dislocated' and within-region costs and benefits

A multiplicity of approaches, both qualitative and quantitative, and social science disciplines (e.g., economics, anthropology, sociology, psychology, human geography, etc.) have bearing on the identification, analysis and integration of potential costs and benefits arising from improved prediction in and outside of the polar regions. Data and resource availability may constrain certain approaches to particular users/sectors (e.g., revealed preference analysis in economic studies). In other cases, methods may not have been evaluated for particular populations or cultures (e.g., use of willingness-to-pay approaches for aboriginal populations) and may not be appropriate. For detailed, place-specific, ethnographic studies, common in anthropological research, issues of representation may be important if findings are to be applied across a large number of settlements. The challenge then is to develop a framework adequate to explore costs and benefits and sufficiently flexible to take advantage of a variety of methods that are available. It may be useful to take, apply and critique an existing approach, for example the "steps to conduct an economic analysis" that has been advocated specifically for examining the economic benefits of national weather services (*Lazo et al. 2008*).

Development of a user application and social science research framework, including the establishment of linkages with verification and other natural science components of the PPP, will be essential to rising to the challenges noted above. Such a framework must explicitly treat the teleconnections between improvements in the prediction of hydrometeorological processes and phenomena in polar and extra-polar regions as this may be the greatest source of economic (though not necessarily social) benefit. It must also acknowledge and account for the important role of indigenous and local knowledge concerning weather-related risks[3] and the interactions of such wisdom with scientific sources of information. As noted by many climate and environmental change scientists (e.g., *Wolfe et al. 2011*), it will likely be critical to directly involve indigenous and local residents in the design and execution of the research if it is ultimately to be of any lasting relevance in applications.

1.4 Key Challenges

- Estimation and analysis of historic and current use of polar prediction products
- Communication of risk, opportunity and uncertainty across user types
- Methods to evaluate and integrate 'dislocated' and within-region costs and benefits.

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[3] For example, Krupnik (2011) systematically reviews and documents hundreds of terms historically used to describe sea ice characteristics by Arctic indigenous peoples

2. VERIFICATION

2.1 Background

Interest in forecast verification activities has grown extensively in recent years along with the development of new, innovative verification techniques. There have been a string of top-level, widely praised verification methods workshops (in Melbourne 2011, Helsinki 2009, ECMWF 2007), including tutorials on verification, high quality verification research is flourishing, and new books on verification have been published (*Wilks, 2011; Jolliffe and Stephenson 2012*). Various other verification activities have likewise been abundant under the WMO umbrella, very much due to the activity of the WWRP/WGNE Joint Working Group on Forecast Verification Research (JWGFVR) (http://www.wmo.int/pages/prog/arep/wwrp/new/Forecast_Verification.html/).

Throughout the years, forecast verification has, indeed, always been accentuated as an integral component in every meteorological research plan, but in practice often covered, at most, the computation of some 500 hPa field forecast RMS errors and anomaly correlations. The verification tool bag of today, thankfully, consists of a varied set of new and innovative diagnostic measures and techniques. The sound trend in verification research and methodology development is expected to continue but should, nevertheless, be fully endorsed. The JWGFVR provides guidance on a wide range of verification methods and metrics at its dedicated website (http://www.cawcr.gov.au/projects/verification/).

Recent progress in forecast verification has seen various diagnostic methods in the form of spatial verification techniques (e.g., *Gilleland et al. 2009*) becoming mainstream. There is a wealth of new categorical verification measures focusing on rare and extreme weather event verification (e.g., *Ferro and Stephenson 2011*). These new approaches, while on the one hand gaining more ground, at the same time desperately await extensive exploratory analysis of their features and appropriateness for given forecast evaluation applications. The increased popularity of probabilistic forecasting applications and ensemble prediction systems has brought about an increasing need for their validation, resulting in the advent of advanced probabilistic verification techniques. Statistical inference, almost totally neglected in the past in association with verification, is becoming a standard procedure.

Some of the biggest challenges in forecast verification relate to the observations and their quality and quantity. Representative observational data are the cornerstone behind all proper and successful verification actions. This is most tangible for high impact and rare weather events characterized by small data samples. Similarly, this will most probably be the overall biggest future challenge for successful forecast verification in polar regions due to the notorious sparseness or even total lack of in-situ observations.

Forecast verification against analyses produced by the model itself is still a common - and often highly questionable — practice, as demonstrated in Figure 3. Especially when, and in the absence of decent observations, the analyses are in essence driven by the model first-guess field. Therefore, there is a fundamental urge to find a synergy between forecast verification and data assimilation (see Section 5) and to investigate what aspects of data assimilation methods might be applicable in verification.

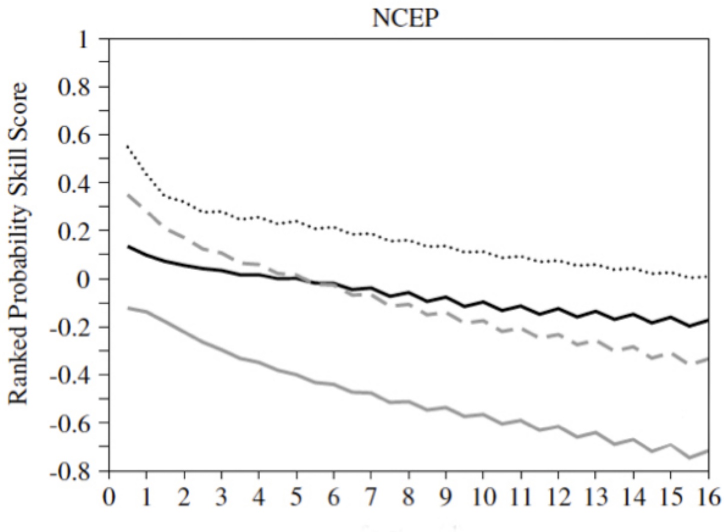

Figure 3 - Sensitivity of probabilistic forecast skill to the analysis used for verification, showing the incestuous nature of using the same model for analysis and verification. Average Ranked Probability Skill Score (RPSS) for probabilistic forecasts of tropical temperature at 850 hPa with the NCEP ensemble prediction system using NCEP's own analyses (dotted), and ECMWF (solid-black), Met Office UK (solid-grey) as well as the multi-centre mean analysis (dashed-grey) for verification, for forecast periods out to 16 days. The larger the RPSS the more skilful the ensemble forecasts are. Based on *Park et al. (2008*)

The potential use of current satellite data for verification purposes is also prone to misleading interpretations of forecast quality due to the properties and quality of satellite data. This is a highly contradictory issue if and when satellite observations dominate the verification statistics. Some of the desirable and necessary properties of verification measures and metrics can be summarized as:

- Their dependency on the verification (analysis) grid should be minimized
- Their dependency on the spatial and temporal scales and sampling of observational data should be minimized
- Their behaviour should not depend on the base value - i.e., the magnitude of the verified variable
- Their behaviour should not depend on the base rate - i.e., climatology
- They should remain useful for rare events, realizing that most conventional verification measures become unusable beyond around the 90 percentile
- They should converge as quickly as possible for small samples
- They should take both hits and false alarms into account when formulated as categorical forecasts
- They should possess high statistical significance and be accompanied by estimates of uncertainty, or confidence intervals
- They should be "proper", "equitable" and not reward "hedging".

In general, the verification strategy needs to be defined taking into consideration the users and based on user needs of forecast information. Therefore, the target users must always be specified when planning and designing a verification system and before performing verification actions in practice, be it model-oriented verification for modellers or final forecasts delivered to end users. The Polar Prediction Project may, at least initially, lean towards model-oriented verification. However, all meteorological research should have as its final goal the development of applications directed towards operational deployment to serve the end users of weather information. It is, therefore, necessary to include verification aspects relating to the expected end users of polar predictions. Verification tailored for end users relates closely to Section 1 of this document.

Sea Ice Verification

As environmental prediction advances and coupled modelling becomes more common, an additional challenge in polar regions is in how to perform the verification of sea ice forecasts. While many of the issues noted above hold true for sea ice forecasting, additional difficulties are introduced by the small-spatial scale and fast timescales upon which sea ice evolves. Indeed, it is upon these scales that forecasts are required both for weather prediction and for the needs of marine navigation. For example, the opening of leads is a chaotic process that occurs on the scale of metres, yet it is important for heat and moisture exchanges between the ocean and atmosphere (and thus weather forecasts) as well as for navigation within the ice pack. In addition, sea ice models are largely untested at the fine scales required for short-medium range environmental prediction and their stress-deformation relations (so-called ice rheology) may not hold at such small scales. However, activities are underway as part of the Arctic Ocean Model Intercomparison Project to evaluate sea ice models at a range of resolutions (*Johnson et al. 2012*). Finally, only a handful of routine ice prediction systems are in place and there has been little published on the verification of these systems to date (*Van Woert et al. 2004*). However, the Global Ocean Data Assimilation Experiment (GODAE) Oceanview project has started a routine intercomparison activity including sea ice that may address this to some extent.

2.2 Key Challenges

The first key challenge will be to define an optimal observing network taking into account forecast verification needs and requirements. A high resolution observing network with remote sensing data nested objectively with available in-situ observations would be highly essential to be able to evaluate forecasts of high-impact polar weather.

Verification methods and metrics need to be tailored and tuned to address requirements specific to the polar environment. This needs to be done both for deterministic and probabilistic forecasts (including ensemble prediction systems) and not excluding user oriented weather elements and phenomena. Verification method development and comprehensive testing of new techniques is hence an integral key challenge in the polar prediction verification. A good baseline is the utilization of the recent recommendations by the JWGFVR for the verification of specific forecasting applications such as precipitation (*WMO, 2009*) and cloud (*WMO, 2012*).

3. OBSERVATIONS

3.1 Background

Observations play a crosscutting role in the context of a coupled polar prediction system. At a fundamental level, it is observations that are used to develop a basic understanding of physical processes that must be modelled within the ocean-atmosphere-land-wave-ice system. Observations are needed for initialization/assimilation, and verification of models and play a key role in improving parameterizations and forecasts. In-situ measurements are required to improve various aspects of satellite retrievals and are the only means to observe the sub-surface ocean. These statements are basic truths whether the forecast system is coupled or un-coupled, polar or global, so it is important to focus on issues (modelling, data assimilation, and ensemble forecasting) particular to the **coupled polar problem**.

Some guidance on this issue comes from considering why we need coupled forecasts. The principal reasons for applying coupled models for short-term (1–15 day) forecasts are 1) the data assimilation process is best formulated in a coupled approach and/or 2) significant coupling between the media occurs on the timescale of the forecast (i.e., coupling effects are degrading the forecast if not properly accounted for). Case 2 situations are typically regional or sub-regional-scale regimes where the physics allows, for example, rapid adjustments in the ocean surface properties. Also, winds, air-sea momentum flux, and surface wave spectra are inherently strongly coupled but are sufficiently correlated that, to date, simple uncoupled parameterizations are widely used. Current *uncoupled* global atmospheric forecast models have 500 hPa thickness anomaly correlations on the order of 98% at 3 days and 90% at 5 days. However, the correlation for near-surface variables and small-scale atmospheric phenomena such as polar lows is much, much poorer. Again, since interfacial exchanges characterize the coupling, it is clear that boundary-layer and interfacial properties are the critical variables for short-term coupled forecasts. As time scales increase, the energy, mass, and momentum balances start to play an increasingly important role so the necessity for coupling increases. The difference in time scales of a single ice floe compared to the overlying atmosphere is illustrated in Figure 4 using a 50-day sample from the SHEBA field programme. However, individual floes are moved and mechanically changed by wind stress and ocean currents at much shorter time scales. Because sea ice is unique to polar regions, sea ice forecasting is, compared to the global problem, key to the polar prediction problem.

A major component of the PPP research activities is the Year of Polar Prediction (YOPP) planned for 2017-2018. This will require a substantial programme to create an archive of necessary observations and model experiments to advance polar prediction capabilities. Recent examples of such an activity include CEOP (Special Issue JMSJ, 2007), TIGGE (*Bougeault et al. 2010*), YOTC (*Waliser and Moncrieff, 2008*), and Concordiasi (*Rabier et al. 2010*). The majority of observations will be global datasets such as NWP re-analyses[4], global satellite retrievals, hybrid/blended data, and standard in-situ ocean, ice, and atmosphere surface sites and soundings. Analysis or reanalysis data represent a dynamically consistent assimilation of most of the global in-situ and satellite observations. Here the principal issue will be creation of a model-friendly archive with strong interactions between modelling and assimilation research groups. Collecting complementary, process-oriented, observational data sets that are independent of numerical models is also crucial, since key non-measured parameters (e.g., energy fluxes) are often in error in reanalyses. These parameters are typically generated by the parameterizations of the numerical model that form the basis of the reanalyses, and are therefore not suitable for use in improving model parameterizations. Such observations also provide important information for the use of satellite data. While weather forecast models assimilate radiance directly and bypass retrieved properties, as the time scale of the forecast/projection increases there is more reliance on retrievals for verification. For example, *Medvigy et al. (2010)* compared climate model values of radiative fluxes and precipitation with satellite retrievals that require surface-based observations for

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[4] *There are also regional reanalyses, such as the Arctic System Reanalysis, 2000-2012, focused on the greater Arctic at high spatial resolution (http://polarmet.osu.edu/ASR/index.html).*

validity. However, data for these 'calibrations' are often lacking for polar regions (see Figure 5, also *Matsui et al. 2012*). This is a recurrent theme for polar research (see Section 3.3).

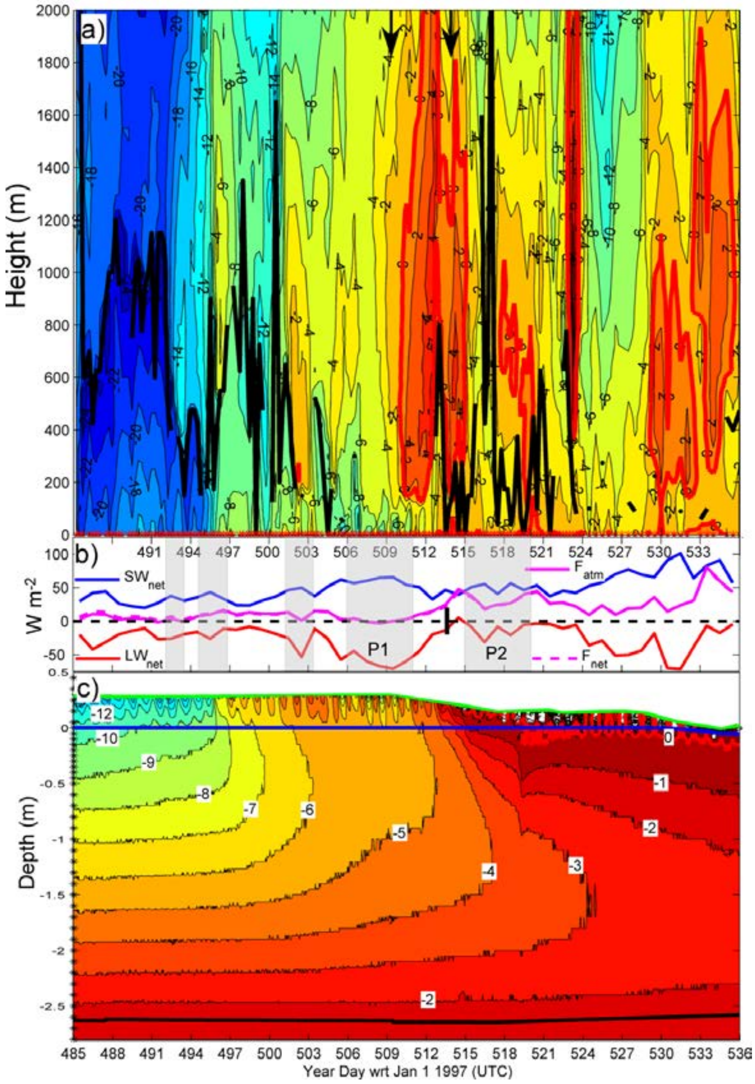

Figure 4 - Temperature in the a) atmosphere and c) snow and ice from April 30 (YD485) to June 20 (YD536), 1998, at SHEBA. Panel b) shows the daily mean net energy fluxes and the time of melt onset (vertical black bar). In a) and c), the 0° C isotherm is shown in bold red and the height of the maximum RH_w for RH_w > 95% is shown in bold black in a). In b), the times of springtime synoptic events discussed are shaded but unlabelled, while periods P1 and P2 are discussed in the original paper. In c), the snow surface is shown by the green line, the snow-ice interface by the blue line, and the ice bottom by the thick black line. Temperatures near the top of the snow may be biased by solar radiation. Note that F_{atm} and F_{net} in b) are nearly identical and the lines are hence mostly indistinguishable (*Persson 2011*)

A major research emphasis of this project will be **regional** datasets with a polar flavour. This will include enhanced observations from existing polar mooring, buoy and atmospheric networks - e.g., IASOA (*Matsui et al. 2012*) and IABP - and expanded/enhanced sub-surface, surface and airborne platforms. Enhancements will include greatly expanded direct flux (turbulent, radiative, precipitation) measurements, clouds, aerosols, and atmospheric/oceanic chemistry. Regional observations that are not assimilated into global and regional models will be essential for verification.

This project will require a major effort in focused process-study observations where the goals will be oriented toward developing process-level understanding and improvement of parameterizations, assimilation methods, satellite retrievals, observing system design and specialty verification data. This aspect will have a polar and/or ice thrust with durations of months to years.

Observing systems design requires a major effort in Observing System Experiments (OSEs) and Observing System Simulation Experiments (OSSEs) - see the whitepaper by *Masutani et al. (2013).*

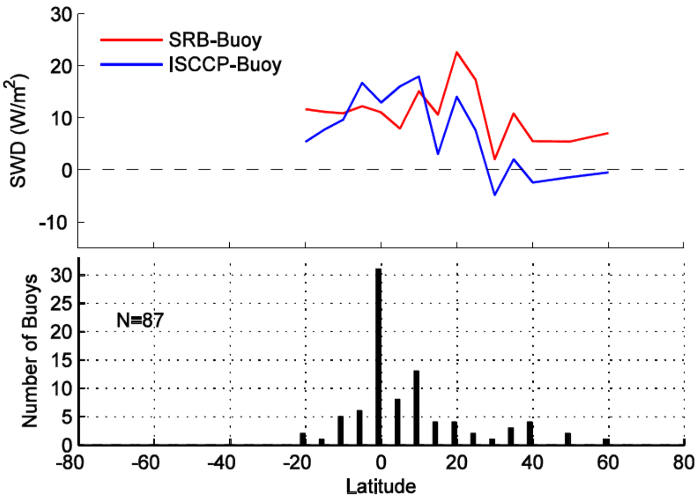

Figure 5 - Differences of mean downward solar radiation satellite products with buoy observations for the last 20 years as a function of latitude: upper panel, mean difference; lower panel, number of buoy sites (*Fairall et al. 2012)*

The polar prediction research project will emphasize model development using **existing and planned** observing infrastructure. Research in the observations realm will principally involve *assimilation*, *data processing techniques*, and *retrieval* work as opposed to efforts to advance observing system hardware (with the obvious exception of deployments for process studies).

3.2 Global Observing System Context

Figure 6 gives an example of the 'impact' of specific components of the current operational **global atmospheric** forecast observation system on a common forecast metric (500 hPa thickness). This particular figure shows the variable impact that assimilation of different observing systems has on the reduction of atmospheric model forecast error. Figure 6 also shows how the global data impacts vary when the source of a particular data type changes (Atmospheric Motion Vectors (AMV) from NRL vs. GEOS-5). Further examination of Figure 6 illustrates the enhanced importance of satellite-based observations for *polar* forecasts where radiosondes are very sparse. Radiosondes and land-surface stations are principally land-based observations and aircraft observations are upper tropospheric except at airports (which are over land).

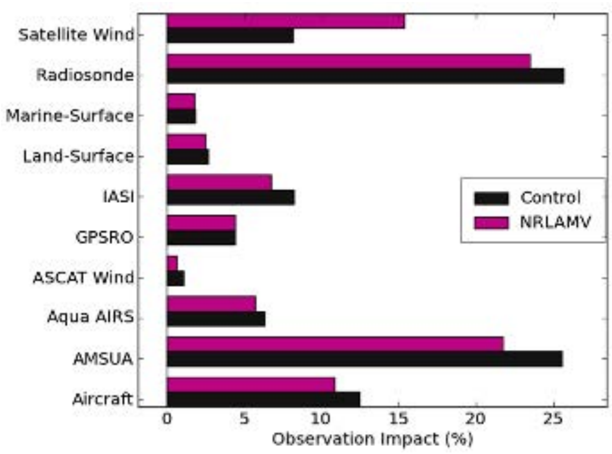

Figure 6 - Fractional observation impacts for forecasts run from December 10, 2010 to January 31, 2011. The control runs (black) made use of the standard GEOS-5 data set, while the NRLAMV runs (magenta) substitute FNMOC AMVs for those normally used in GEOS-5

We find similar variable data impacts of **ocean** observing systems on reducing ocean model forecast error. Figure 7 shows adjoint-based data impacts of profiling data types in the US Navy's global HYCOM system. Here we are looking at the impact of temperature data assimilated on reducing HYCOM 48 h forecast error in the Atlantic basin.

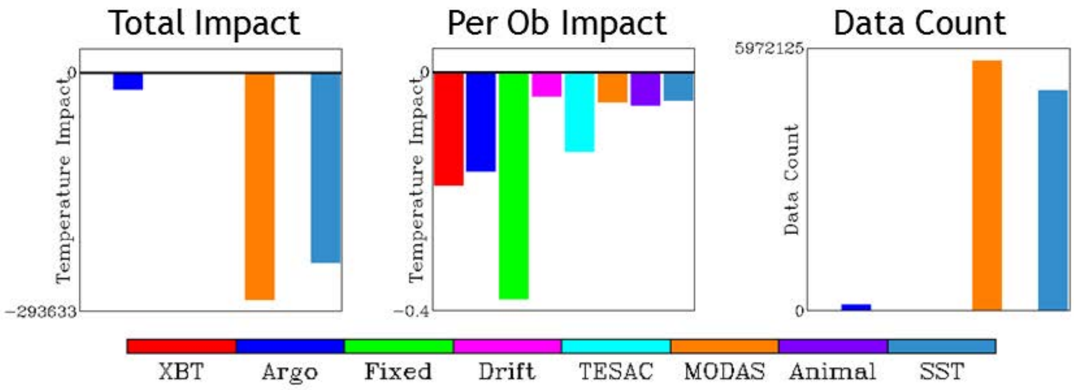

Figure 7 - Histogram plots of impact of temperature data in global HYCOM Atlantic basin domain for October through November 2012. A negative value indicates a beneficial data impact (assimilation of that data type reduced forecast error). Similar results are found for other ocean basins (Indian, Pacific, Arctic).
XBT: expendable bathythermographs; Argo: Argo profiling floats; Fixed: fixed buoys; Drift: drifting buoys with thermistor chains; TESAC: CTD, ocean gliders; MODAS: synthetic temperature profiles from altimeter SSH; Animal: animal borne sensors; SST: satellite and in-situ sea surface temperature

Total data impacts are dominated by the most numerous data types, which are the satellite altimeter SSH and satellite SST observing systems. However, when normalized on a per observation basis, in-situ data types such as the tropical mooring arrays (TAO/TRITON, PIRATA, RAMA) are found to have the greatest impact. This result is due to large HYCOM model error at low latitudes. The HYCOM model needs to be consistently constrained in the tropics at depth, and the sampling strategy of the tropical moorings is ideally suited for this purpose. Although not shown here, it is also possible to look further at data impacts in terms of day or night retrievals and retrieval resolution (1-km LAC vs. 4-km GAC). Note that these data impact assessments will be readily available for both the ocean and atmosphere assimilation components of the coupled forecasting system and should be extended to include sea ice assimilation as well.

3.3 Polar Focus

Calder et al. (2010) reviewed the current state of the Arctic observing system (ocean, ice, air) and *Rintoul et al. (2012)* the Southern Ocean Observing System, discussing various issues and gaps. *Lazzara et al. (2012)* discuss the Antarctic automated weather station programme. It is apparent that oceanic and atmospheric observations are, with the exception of polar satellite sensors, significantly less for the polar regions. This is profoundly illustrated in Figure 8, which shows ocean profile information available to assimilation in operational ocean forecast models.

In the near future, improvements in technology, deployment, and sampling are anticipated. *Bourassa et al. (2012)* describe an approach to expand and improve in-situ and satellite near-surface flux observations at high latitudes. *Kwok et al. (2010)* describe a combined altimeter and bottom-pressure sensor approach for polar ocean observations, and *Lee et al. (2010)* describe new plans for autonomous profilers (see also *Kikuchi et al. 2007*). New prospects for ocean observing technology are described in *Fairall et al. (2012).*

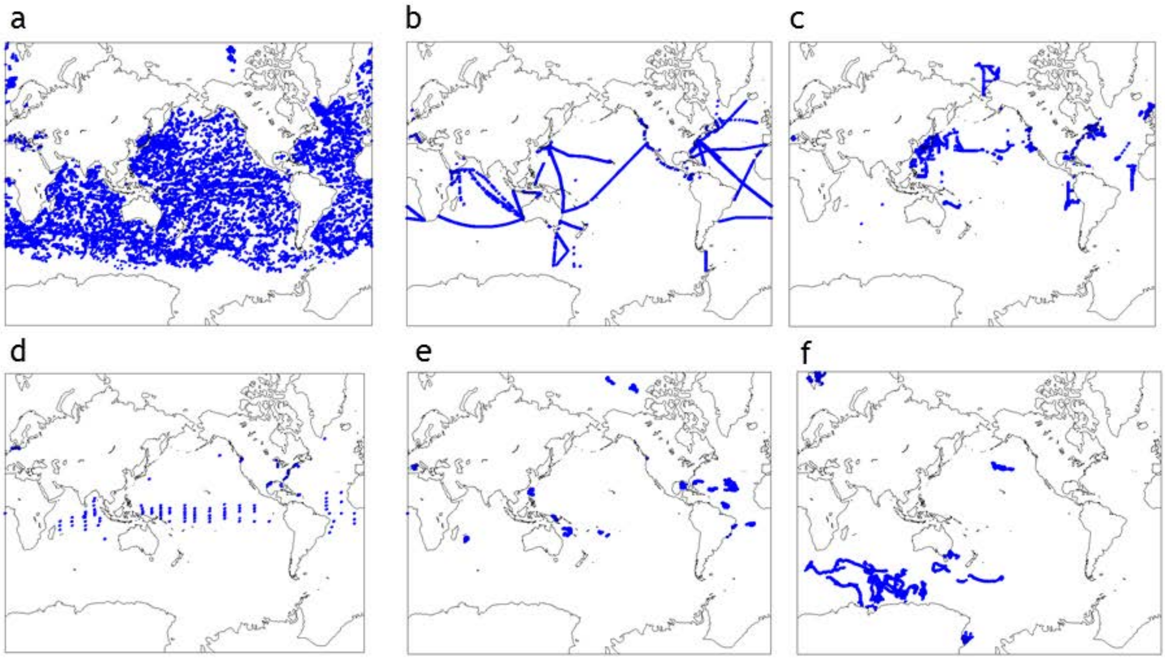

Figure 8 - Data coverage of profiling data types for September through November, 2012. (a) Argo, (b) XBT, (c) TESAC, (d) fixed buoys, (e) drifting buoys with thermistor chains, (f) animal borne sensors. TESAC is a WMO code form and includes CTD and ocean glider observations

Even though polar orbiting satellites provide excellent coverage over the poles, instruments and data assimilation techniques are not optimized for polar areas. The shallow atmospheric structures with a focus on boundary layer and lower troposphere, the lack of optical and thermal contrast between atmosphere and surface, and fast changing conditions near the ice edge are not well resolved by satellite observations and not well represented in the statistical characterization of model and observation uncertainties in data assimilation.

The YOPP (2017-2018) will be the keystone of a focussed intensive international effort to obtain greatly enhanced polar observations. This effort will include one or more multi-year sea-ice based observing stations (currently using the name MOSAiC), greatly enhanced deployment of autonomous samplers, enhanced monitoring from routinely deployed polar ships, and coordinated intensive field studies from research vessels, aircraft, and surface stations. An example of combined surface-based and airborne observations combined with regional model fields of cloud properties is shown in Figure 9 to illustrate one approach to improving model parameterizations *(Solomon et al. 2009).*

Similar work has been done with regional and climate models (*Liu et al. 2011*) and satellites (*Kahn et al. 2011).* The emphasis will obviously be on strongly polar topics such as sea-ice dynamics, ocean waves in the presence of sea ice, effects of black carbon on the surface energy budget, shallow/stable boundary layers, etc.

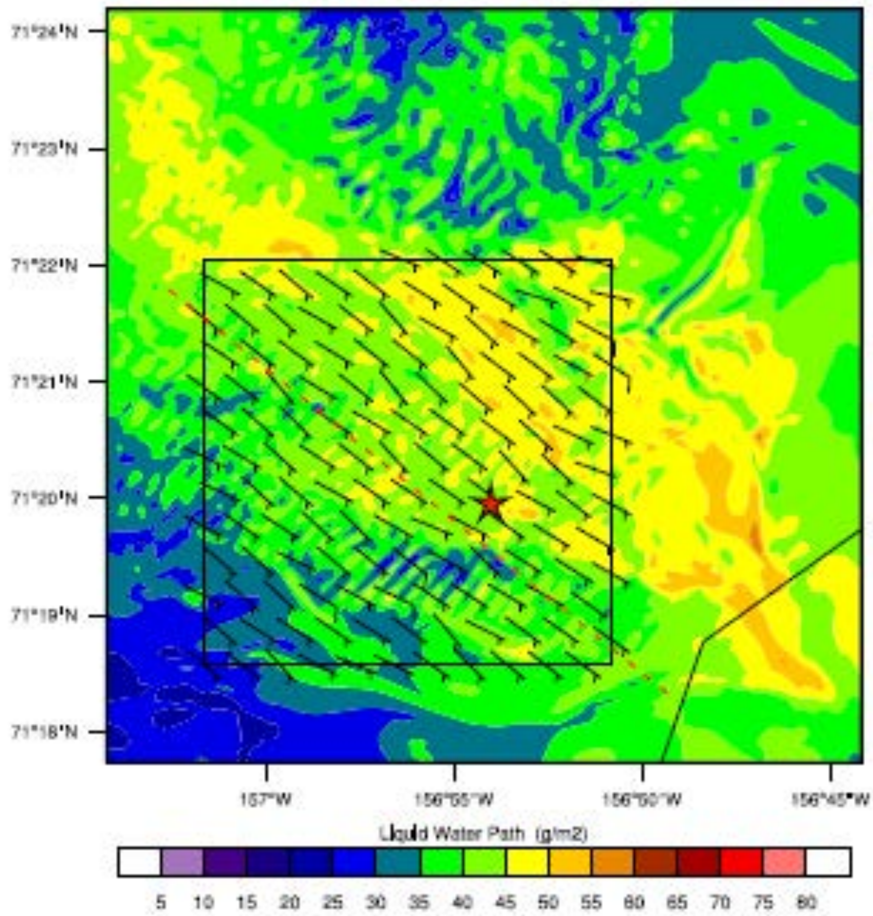

Figure 9 - Liquid water path (colour) and winds (flags) at maximum liquid water level at 20 Z on 8 April 2008 for the 50 m nest LES simulation. A half barb on the wind flags indicates 5ms^{-1} and a full barb 10ms^{-1}. The square marks the region used to make total, downdraft, and updraft averages (130×130 grid points). The red star marks the location of vertical profiles used for model-observation comparisons. Barrow, Alaska is located directly to the east of the red star, to the right of thin black lines in the lower right marking the Alaska coastline. From *Solomon et al. (2009)*

3.4 Key Challenges

The scarcity of observations, the unique balance of physical processes, the key importance of sea ice, and the rapidly evolving climate of Arctic lead to a number of scientific challenges for observations in the context of a polar prediction system. Some examples are listed here:

- Coupled Polar Prediction is strongly sensitive to errors in fluxes across the surface interface and thus requires collocated information about the state of the atmosphere, sea ice and ocean.
- Polar surface properties are often dominated by various forms of ice that vary rapidly on small spatial scales. Some remote sensing methods of ice properties (ice cover, ice thickness, snow depth on ice, albedo, crystal structure) are not mature and offer little information from within the ice, whereas in-situ methods are poorly sampled. Neither is currently able to address the need for high spatial and temporal resolution observations of sea ice deformation over large regions. Observations providing information regarding ice deformation and redistribution during ridging are also lacking.
- The presence of a seasonal ice cover limits the use of Argo profiling floats in polar regions. While several alternative technologies have been developed (ice tethered profilers, gliders communicating via acoustic modems) a comprehensive real-time ocean observing network able to supplement Argo for polar regions has yet to be put in place, hindering the progress toward coupled polar prediction.

- Polar regions are dominated by stable surface layers and very shallow boundary layers that place an extreme demand for accurate near-surface meteorology and fluxes. This more limited vertical scale also complicates the horizontal spatial sampling problems. Surface temperature, humidity, clouds and winds are all important.
- Polar weather forecasting is more difficult because of the predominance of mesoscale phenomena with small horizontal and vertical scales; large horizontal variability in stability, temperature and surface characteristics; large vertical variability in stability, temperature, and humidity; smaller-scale systems with rapid development (polar lows, heavy snow from embedded convection and topographic effects, low-level fronts and jets, mountain lee waves trapped under inversions). This smaller scale requires denser observations with finer vertical resolution than used at lower latitudes where many important systems are very large scale, well-mixed vertically, and slowly evolving (e.g., the Madden-Julian Oscillation).
- Improved information on the combined statistical aspects of the environment and observing system is required for variational and ensemble data assimilation approaches, and bias correction schemes. This will require a programme of special high-quality reference observations targeted to specific parts of the problem.
- The surface energy balance in polar regions is often dominated by radiative fluxes, which are very sensitive to the partitioning and properties of liquid, ice, mixed-phase clouds and the vertical thermodynamic structure of the lower troposphere. Current global observation technologies offer poor discrimination of these properties.
- Important observations (such as operational balloon soundings) tend to be limited to populated areas, which leads to biases toward lower latitude coastal regions. The present observing system represents convenience and cost efficiencies rather than a scientifically conceived structure to observe the key phenomena. Optimization of the observing system for the coupled prediction problem, and expanded routine observations over the high polar regions, will be critical.
- Aerosols play an unknown role in direct and indirect radiative forcing in polar regions. Details of polar aerosol transport, production, and consumption are largely unknown. Is there good aerosol predictability in the present global structure? Or, will the possible role of local oceanic chemical or biological sources require observations?
- Precipitation rates tend to be weaker in polar regions relative to lower latitudes and are dominated by complex ice and mixed-phase microphysical processes. Current treatment of precipitation in global models tends to be dominated by strong convective mechanisms that are not appropriate in polar regions. Improvements to polar precipitation modelling will require observational methods to discriminate cloud/precipitation properties from satellites, airborne, and ground-based remote sensing systems.
- Polar predictions may be more sensitive to assimilation of some atmospheric or oceanic variables that play a secondary role in global predictions. These variables need to be identified and the ability of the observing system to provide the variables with sufficient accuracy needs to be evaluated. Example - ozone profiles.
- The lack of synoptic lower tropospheric in-situ observations over the Arctic Ocean severely limits the Arctic forecasting ability. The Arctic Ocean represents a unique area the size of the United States over which no regular rawinsonde data are collected, and where satellites are unable to provide even basic meteorological measurements in the key lower troposphere.
- Conditions are changing rapidly with the loss of summer sea ice extent and the balance of physical, chemical, and biological processes is evolving. Phenomena long considered negligible in the Arctic may be becoming important (e.g., ocean waves — *Cavaleri et al. 2012*).

4. MODELLING

4.1 Background

Physical, dynamical and chemical processes in the polar regions are less well captured in models than they are at mid-latitudes, with critical consequences for the predictability on all time scales. The polar regions experience special conditions such as stably stratified long-lived boundary layers, optically thin clouds and rapid development of polar lows. At other times, when the large-scale forcing is weak, there can be a delicate interaction between several small-scale processes such as turbulence, aerosols, cloud microphysics and radiation, which in the end determines the energy fluxes at the surface. Furthermore the surface is to a large extent covered with ice and snow, surfaces that evolve even at relatively short times scales in response to the surface fluxes. This highly interactive nature of both processes within the lower atmosphere and interactions between the atmosphere and the surface requires "integrated thinking" and, perhaps, a more integrated approach to parameterization development.

Many of these processes - boundary layer phenomena, cloud microphysics, gravity wave drag, radiation and surface exchange — are sub-grid scale and thus parameterized in models. Parameterizations used in models today are not developed and optimized for polar regions rather for the mid-latitudes where the required observations are generally more available. The sparse observations from the polar regions show that the conditions are frequently outside the range observed in other regions.

Surface parameterizations used in forecast models are constructed using observations taken over horizontally homogeneous surfaces and are assumed to be in quasi steady state with the atmosphere above. Major uncertainties arise when representing the mean flux for a model grid square when it contains a mixture of surfaces. This is referred to as the flux blending problem which is not limited to the polar regions. However, it may be of particular important over the polar oceans sea ice in winter when leads have a disproportionate effect on energy fluxes. Parts of the Arctic (Greenland and Alaska) and the Antarctic have very complex terrain with gravity waves, orographic jets and katabatic winds as characteristic phenomena.

Atmospheric phenomena in the polar regions are commonly smaller in horizontal and vertical dimension than elsewhere and the tropopause in generally at a lower altitude. Examples are polar lows, shallow boundary layers and katabatic flows. Thus representation in the polar regions would benefit from increased resolution both horizontally and vertically.

The large-scale forcing (e.g., from Rossby Waves) is generally weaker in the polar regions and varies over the year. The solar forcing is not sufficient to provide a strong diurnal cycle but instead has a very strong annual cycle. Changes in surface properties can, however, exert quite strong forcing even at short time scales (sea ice or open ocean, snow or bare land, fresh or wet snow) which calls for coupled models. For longer time scales the importance of coupling sea-ice, ocean, snow, permafrost and river runoff with the atmospheric component of a model increases.

4.2 Surface Processes

Figure 10 (from *Bourassa et al. 2013*) provides an overview of surface fluxes and related processes for high latitudes.

Characterization of the nature of the surface is critical to parameterization of the exchanges between the land/ocean surface and the atmosphere. The exchanges are essentially specifications of turbulent fluxes of momentum, sensible heat and moisture as well as radiation, aerosols, and trace gases. These fluxes change the surface properties and will affect the state of the atmosphere and ocean - i.e., the numerical problem is highly coupled. At diurnal time scales the interface temperature will often change significantly over land or sea ice in response to shortwave and longwave radiative changes. As prediction time scales increase, the evolution of the surface and subsurface states become increasingly critical.

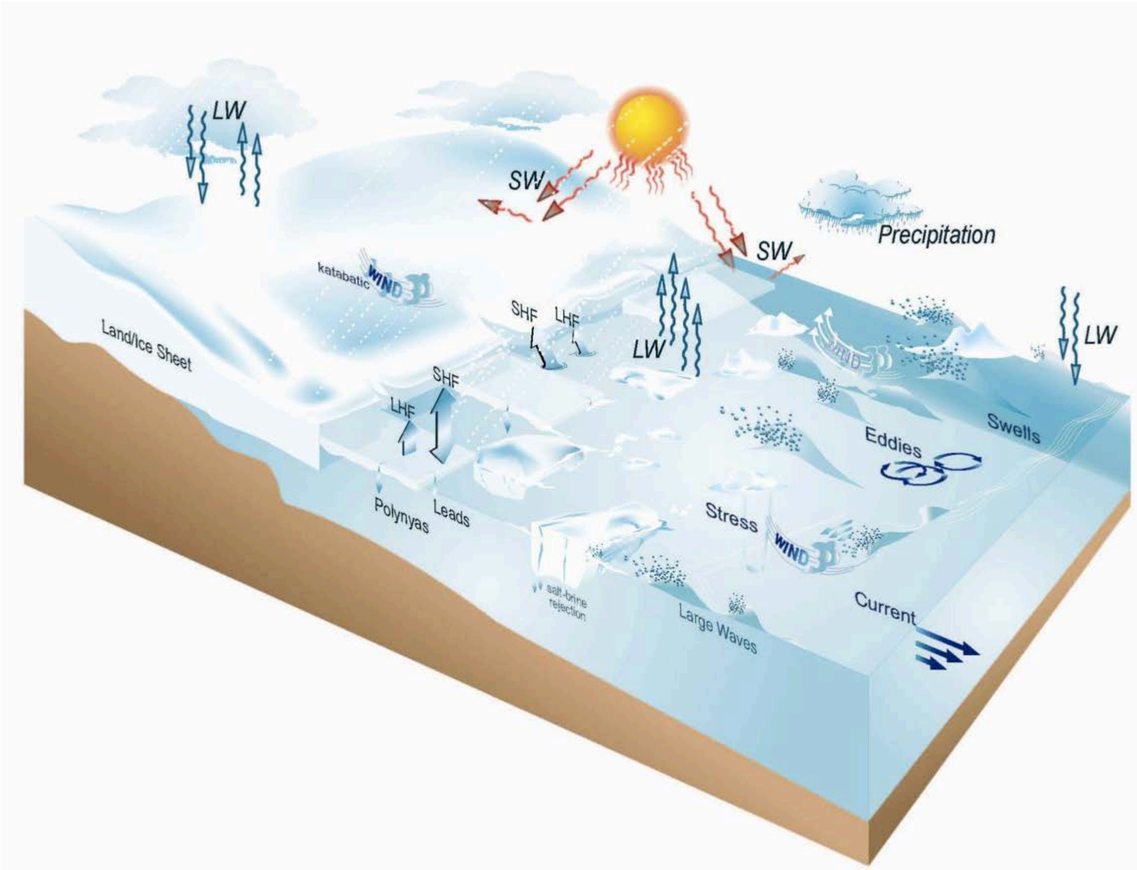

Figure 10 - Schematic of surface fluxes and related processes for high latitudes. Radiative fluxes are both shortwave (SW) and longwave (LW). Surface turbulent fluxes are stress, sensible heat (SHF), and latent heat (LHF). Ocean surface moisture fluxes are precipitation and evaporation (proportional to LHF.) Processes specific to high-latitude regimes can modify fluxes. These include strong katabatic winds, effects due to ice cover and small-scale open patches of water associated with leads and polynyas, air-sea temperature differences that vary on the scale of eddies and fronts (i.e., on the scale of the oceanic Rossby radius, which can be short at high latitudes), and enhanced fresh water input associated with blowing snow.
From *Bourassa et al. (2013*)

Ice fraction, snow extent and properties as well as state of melt are critical parameters for interaction between the land/ocean surface and the atmosphere. Ice fraction is affected by convergence/divergence patterns in wind stress and currents; ice mechanics and thickness play a direct role. Melt is tied up in synoptic meteorology through cloud/radiative coupling. Predictions of these properties on sub-seasonal time scales are extremely difficult. In marginal ice zones, ocean surface waves are important for ice evolution.

For the shortwave (solar) radiative exchange the albedo of the surface is critical and inter-model differences are large (*Porter et al. 2011*; Figure 11). The presence of sea-ice alters the albedo considerably, even more if the ice is covered with snow. Ice fraction and snow cover (both over land and ocean) are thus critical parameters to be described correctly. Onset of melt season and how the albedo changes with melt (melt ponds versus runoff) are major issues. Deposition of aerosols such as black carbon may also slightly alter the albedo, likely most important during Arctic spring. For the longwave (thermal) radiative exchange the emissivity of the surface is of importance, although this is fairly similar over different surface types and is thus not a problem. Critical for long-wave radiative exchange is the temperature of the surface and the magnitude of the conductance or ground heat flux. Isolating snow layers effectively decouple the atmosphere from heat sources below; thus, ice fraction and snow depth are important parameters.

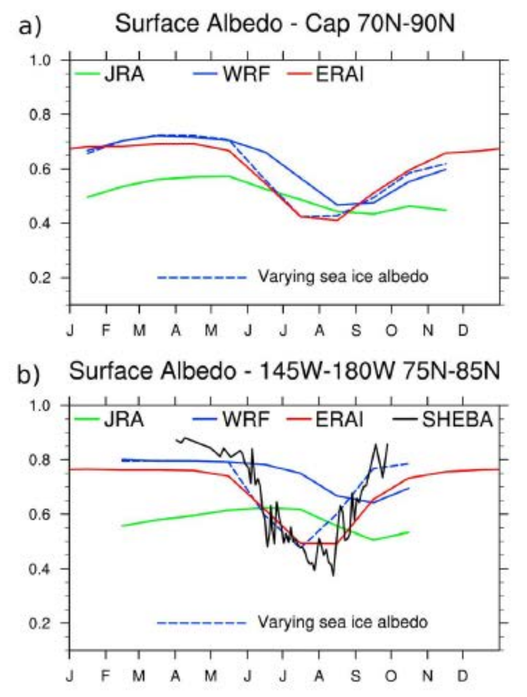

Figure 11 - Annual cycle of (a) polar cap averaged surface albedo, and (b) a comparison of line-integrated SHEBA observed surface albedo for the region from 75N to 85M and 145W to 180W in WRF, JRA-25 and ERA-I. Results from the varying sea ice albedo simulation (dashed blue line) are only for a single year (2001), while the control WRF and reanalysis values are 6 year averages. From *Porter et al. (2011*)

A long history of observations and attempts to parameterize surface turbulent fluxes over the ocean exist. The vertical flux (rate of surface exchange) of some variable, *x*, takes the form:

$$\overline{w'x'} = C_x U_a (X_s - X_a)$$

where U_a is the mean wind speed and X_a is the mean value of *x* at some reference height a in the atmosphere. X_s is the mean value of *x* either at the interface or some reference depth below, while C_x is a transfer coefficient that characterizes the surface and the near-surface static stability. Momentum, sensible heat, moisture, trace gases, and aerosol deposition can all be treated with this formulation. For trace gases, the gas solubility affects both C_x and X_s. The case of a surface source of aerosols is more complicated, since the surface can simultaneously be both a source and a sink, although through different processes.

The transfer coefficient for open ocean is known, on average, to reasonable accuracy for moderate wind speeds up to at least 15 m s^{-1} but is considerably less well known at higher and very low wind speeds. Coupled air-wave-ocean models can be used to directly compute the momentum transfer. This technique is currently under investigation and there is considerable numerical difficultly with the approach. Polar regions would likely benefit from this technique since strong storms dominate the meteorology in the polar wintertime.

4.2.1 Boundary Layers, Orographic Effects and Large Scale Atmospheric Circulation

The science community faces longstanding problems of correctly representing stable boundary layers, an issue highly important for the polar regions where these conditions may exist for long periods (not disturbed by the diurnal cycle) and are at times extremely stratified. Regardless of the near-surface stratification that often is near neutral, the Arctic lower atmosphere is characterized by the semi-permanent Arctic inversion caused by inflow of warm air from lower latitudes at mid-levels. A proper representation of turbulent processes and surface exchange is known to be essential for the quality of both short- to medium-range weather prediction as well as for climate modelling. The problems with stably stratified boundary-layer parameterizations are general (*Cuxart et al. 2006; Svensson et al. 2011*) mostly because the turbulence in these layers are less connected to the local surface conditions with the consequence that the commonly used Monin-Obukhov theory does not apply. Most large scale atmospheric models utilize rather diffusive boundary layer schemes resulting in stable boundary layers that are less stratified, too thick, underestimate the strength of the jet (*Cuxart et al. 2006; Svensson et al. 2011*), and show too little wind turning (*Svensson and Holtslag, 2009*). An example is shown in Figure 12 from *Beljaars (2012).*

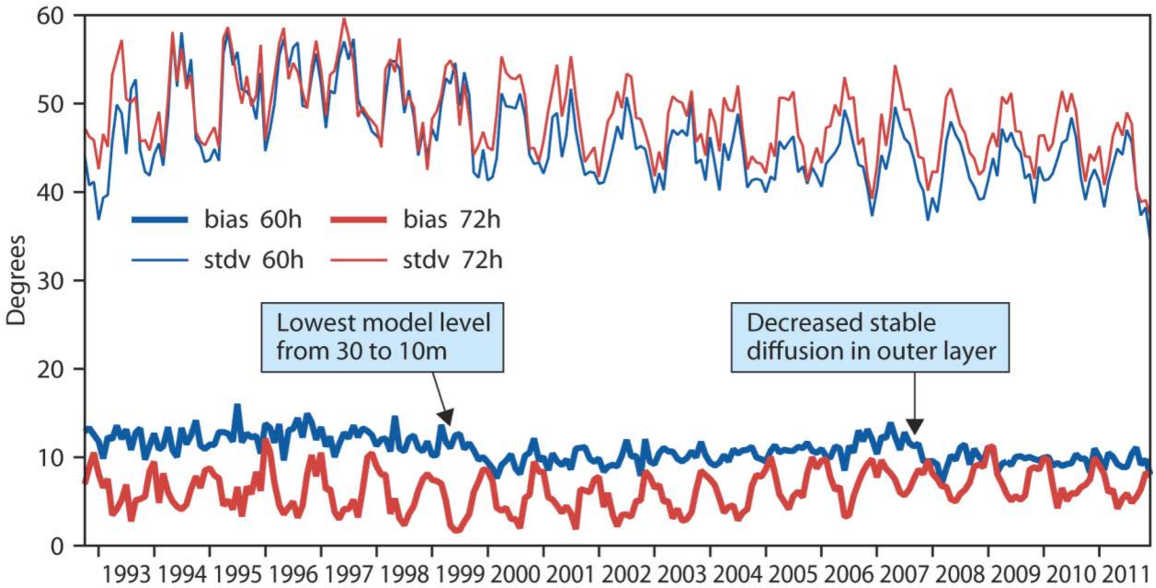

Figure 12 - Historic evolution of 10m wind direction errors of the operational ECMWF system. These are monthly values of mean and standard deviation of errors for step 60 and 72 h forecasts initialized daily at 1200 UTC, verifying at 0000 UTC (blue) and 1200 UTC (red) respectively. The verification is against about 800 SYNOP stations over Europe (30°N-72°N/ 22°W-72°E). From *Beljaars (2012)*

Models show a great sensitivity in, e.g., near surface temperature to small changes in the parameters chosen for stable conditions - see Figure 13. This sensitivity is even increase as other model physics are improved (*Beljaars, 2012*). When the diurnal forcing is weak, as is common in the polar regions, these excessive mixing schemes give rise to significant biases in surface fluxes and other near-surface parameters (*Tjernström et al. 2005; Birch et al. 2009; Renfrew et al. 2009a; Bromwich et al. 2013).*

Motivations for using schemes with more mixing than local observations support are that they take into account fluxes caused by, e.g., meso-scale variability, surface and terrain heterogeneity, and also that they might partly compensate for biases in downwelling long-wave radiation. Using parameterizations based on local observations can lead to unwelcome side-effects, such as decreased forecast skill both locally and remotely (e.g., *Brown et al. 2008*), suggesting there are intrinsic problems with the parameterization that cannot be resolved by simply tuning the models. Furthermore, sensitivity experiments varying the drag over land show a direct impact on the planetary scales in terms of storm track position and blocking frequency (e.g., *Sandu et al. 2012*). The interaction between the boundary layer dynamics and the large scale flow is not well understood. Gravity-wave drag and sub-grid scale orographic drag are key parameterized processes, but the parameterization schemes are difficult to evaluate. The uncertainty in the momentum budget is large in models and needs further attention.

Greenland and Antarctica are massive large scale mountainous plateaus and both have a significant impact on the atmospheric conditions in their respective areas (e.g., *Parish and Bromwich 2007*). To capture the flow in these regions with rugged orography and steep coastal slopes, high resolution simulations are necessary. Blocking effects, gravity-wave drag, katabatic winds, rotors, barrier jets, tip jets, and coastal jets are all phenomena that are important to capture accurately for successful forecasts both for their impact on the large scale flow in general, but also on the local flow and weather (e.g. *Renfrew et al. 2008*). There is a clear link between the boundary layer dynamics and steep terrain which might call for new parameterization methods for the boundary layer in steep orography.

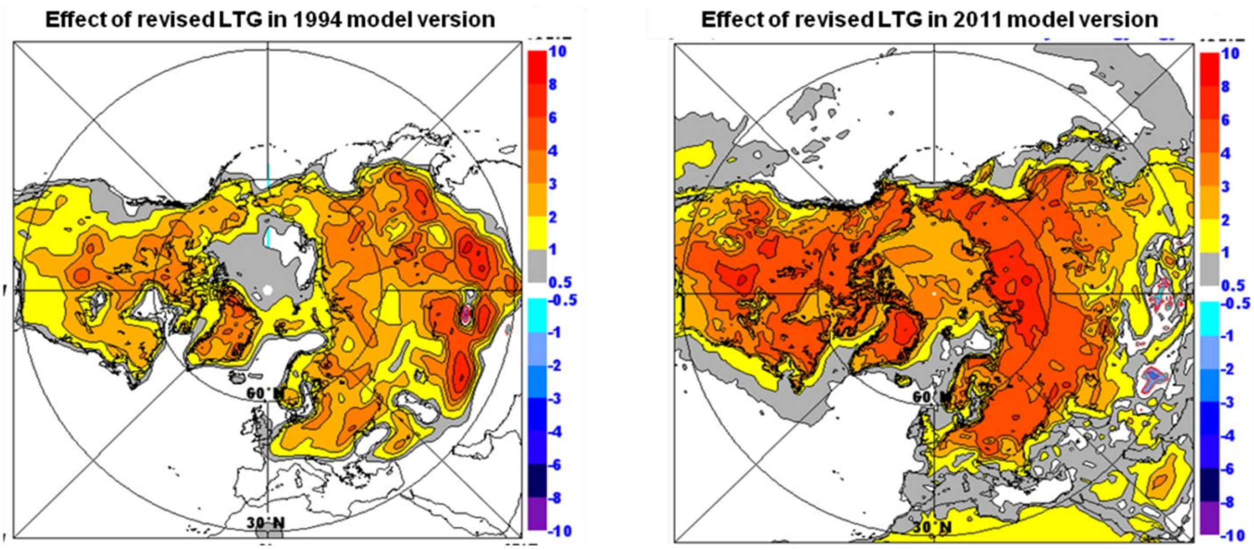

Figure 13 - Mean 2 m temperature effect on averaged January 1996 temperature by varying the model stability functions in the ECMWF model versions of 1994 (left) and 2011 (right). These sensitivity experiments were performed by starting a long integration from 1 October 1995 and applying relaxation to the 6-hourly operational analyses above 500 m from the surface. This is an efficient way of doing "deterministic" seasonal integrations without constraining the stable boundary layer. From *Beljaars (2012)*

In addition, polar boundary layers frequently contain clouds which regulate the exchange of short- and long-wave radiation. Many models are biased in the long wave downward radiation even in clear sky situations which might be linked to too coarse vertical resolution to resolve temperature and moisture gradients near the surface. The specific humidity often increases with altitude over the Arctic inversion. Observed low-level clouds over the Arctic Ocean are in general not topped by an inversion, as is the case with sub-tropical marine clouds; they often extend into the inversion layer (e.g., *Sedlar et al. 2012*). Thus, boundary schemes need to consider the presence of clouds and the coupled system of turbulence, surface fluxes, cloud microphysics, aerosols and radiation has to be dealt with all together.

4.2.2 Clouds and Aerosols

Clouds are notoriously difficult to properly represent in prediction models for all time scales and there are additional challenges when it comes to the polar regions. Especially in the Arctic, low-level clouds are a dominating feature, with climatological cloud fractions ranging from 60-80% in winter to >90% in summer (e.g., *Sedlar et al. 2012*). The polar atmosphere can be extremely cold but there is a prevalence of mixed-phase low-level clouds in all seasons (even at temperatures below -30°C; e.g., *Intrieri et al. 2002; Prenni et al. 2007*). In the Arctic, mixed-phase clouds dominate in all seasons (*Shupe et al. 2011; Shupe 2011*). Many models currently use a temperature threshold to distinguish between the formation of ice or water in clouds. Observations and high resolution models have shown there is no such simple threshold value. There seems to be great sensitivity to the concentrations and relative amounts of cloud condensation nuclei (CCN) and ice nuclei (IN).

The ocean is an important source of primary aerosols and CCN via sea spray from breaking waves. Recent reviews indicate this source is uncertain to about a factor of 5 and there is controversy on the most physically relevant scaling variables (wind speed, whitecap fraction, breaking wave energy dissipation, wave age). At very strong winds (>25 m s^{-1}) sea spray may significantly affect the near-surface thermodynamics and heat fluxes. There are also clear evidence that organic components from biological activities contribute substantially to atmospheric aerosol in the polar environments. Understanding the significance of these biological particles and associated biogenic volatile compounds (e.g., DMS for atmospheric processes and air-ice-snow interfaces is of importance (*Shepson et al. 2012*).

Aerosol-cloud interaction is not well understood and is not represented in most forecast models, neither is the direct effect of aerosols. The difference between the Arctic and Antarctic are large both regarding cloudiness and aerosol amount (e.g., *Bromwich et al. 2012*). The seasonal and synoptic variations in aerosol amount, especially in the Arctic, are substantial. Near the surface, the aerosol concentrations in the boundary layer are typically very low in the summer while advection from the south brings anthropogenic aerosols at other times and heights. Arctic low-level mixed-phase clouds have been shown to be highly sensitive to aerosol characteristics (*Morrison et al. 2008*) but are also greatly influenced by internal cloud dynamics in a complex system (*Morrison et al. 2012*) – see Figure 14. The Antarctic, however, is a very remote region with hardly any anthropogenic aerosols and thus natural sources of sea salt and formation of particles from gaseous emissions from the ocean, e.g., DMS, play a larger role. In both regions during very cold conditions and limited numbers of aerosols there occurs the formation of diamond dust (clear-sky precipitation).

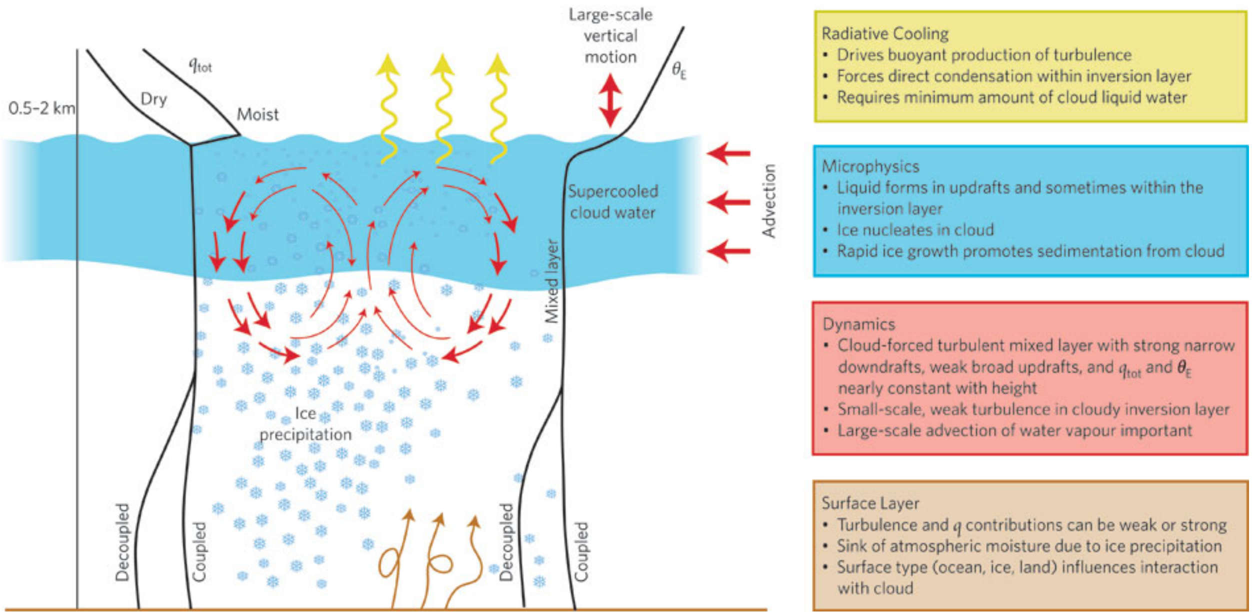

Figure 14 - Illustration of Arctic mixed-phase cloud and processes important for their existence. Characteristic profiles are provided of total water (vapour, liquid and ice) mixing ratio (q_{tot}) and equivalent potential temperature (θ_E). Cloud-top height is 0.5–2 km. Although this diagram illustrates many features, it does not fully represent all manifestations of these clouds. From *Morrison et al. (2012)*

To treat the aerosol impacts, it is likely one requires the use of two-moment microphysics schemes, that forecast a measure of the cloud particle size distribution in addition cloud substance amount. As a caveat, numerical weather prediction with these advanced schemes does not necessarily result in improved forecasts. More field work on the aerosol-cloud physics is required to unravel the linkage.

The cloud radiative effect is, both at the surface and the top of the atmosphere, highly dependent on droplet/ice microphysics which is tightly coupled to aerosols (*Gettelman et al. 2010*). Most of the year the surface cloud radiative effect is due to the longwave component, which is quite sensitive to the phase of the cloud condensate (water, ice, mixed phase). In summer the shortwave component also come into play and due to the surface albedo there are substantial difference in cloud radiative effect over ice versus water. Arctic clouds are suggested to be particularly susceptible to changes in the aerosol particle composition and concentrations, both because these clouds tend to be optically thin and because of the relatively low levels of background aerosol concentrations. Some observation suggests (e.g., *Mauritsen et al. 2007*) that the indirect aerosol effect may in the summer Arctic lead to a surface warming, rather than the opposite as is believed e.g. for subtropical clouds, since the effect on the longwave radiation by changing the cloud emissivity for optically thin clouds overrides the shortwave cloud-albedo effect.
Furthermore, polar aerosol concentrations are dependent on cloud/precipitation processes (*Bourgeois and Bey, 2011*). A great deal has been learned from recent major field campaigns (SHEBA/FIRE – *Uttal et al. 2002, ISDAC – Earle et al. 2011, MPACE – Verlinde et al. 2007*) and the use of high resolution cloud resolving models with full bin-microphysics. There is great sensitivity to the parameterizations in GCMs (*Gettelman et al. 2010*) and the high resolution models show major issues with current parameterizations: a lack of a simple relationship to characterize ice riming rate (*Fan et al. 2011*); or, extreme sensitivity to fall velocity.

Deep convection does not really occur over the Arctic Ocean and the Antarctic continent or sea ice, except for possibly in frontal weather systems. Intense but shallow convection, however, is frequent over open water (e.g. leads or polynyas) in winter and contribute disproportionally to the vertical fluxes. Convection is also very important over the adjacent open seas, when cold polar air encounters areas with relatively warm water (e.g., in cold air outbreaks). Stratocumulus clouds manifested as cloud streaks are common some distance downstream from the ice-edge and these clouds often group into convective clusters, or sometimes polar lows, further downstream, producing huge amounts of snow with high intensity and very poor visibility. They are therefore a major forecasting issue. There is a need to refine convective schemes for high latitudes. Present convection schemes are basically developed for the tropics and middle latitudes and even though they are based on physical principles, they may have to be retuned or reformulated in order to work for polar regions.

4.2.3 Coupled Modelling

The atmospheric circulation in polar regions and thus forecasts on all scales, depends on other media – ocean, sea-ice, river runoff, lakes. Their relative importance varies with forecast time. Using an ocean/sea-ice model coupled with a regional atmospheric model has recently been shown to have a positive impact on atmospheric predictability even for short term forecasts (*Pellerin et al 2004*; see Figure 15).

In addition, it has been shown that coupled forecasts are quite sensitive to the specification of the marine initial condition (in particular sea ice thickness and snow depth) and the model resolution. The sea-ice model needs to be able to respond to rapid atmospheric changes and be able to predict small scale features like leads, cracks and ridges (e.g., *Lipscomb et. al. 2007*), which are of importance for atmosphere-ocean interaction (*Esau, 2007; Marcq and Weiss, 2011*). Such forecasts are by themselves of great interest for society — e.g., shipping or industry activity.

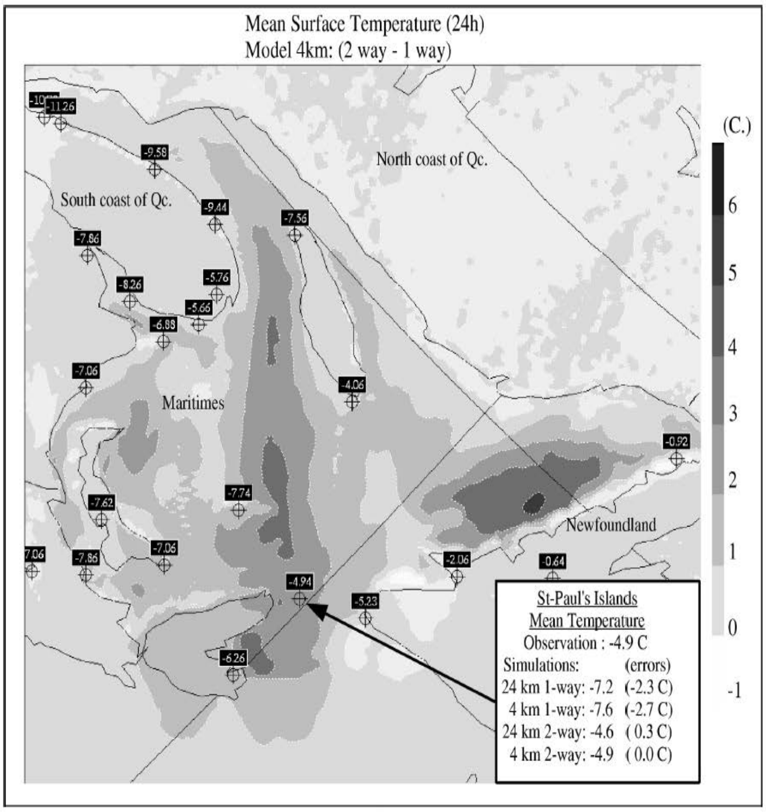

Figure 15 - The difference between the two and one-way coupling simulations (4 km) for the surface temperature averaged over the last 24-h forecast corresponding to 14 March 1997. Labels represents the observations for the same period. Most of the domain has been warmed up by the two-way coupling simulation.
From *Pellerin et al. (2004)*

Figure 16 shows an example of the performance of the regional coupled atmosphere-ocean-ice modelling system for the Gulf of St. Lawrence (GSL) that is run by the Canadian Meteorological centre (CMC) - *Faucher (2011)*. The system operates separate data assimilations systems while the forecasts couple the Global Environmental Multiscale model (GEM) with the ice-ocean model MoGSL through the exchange of surface variables and radiation fluxes at each GEM time step. The forecasts rely on producing a balanced initial state and thus to improve the analysis of ice concentration, ice thickness and snow, all of which contribute to improved forecasts (coupled and uncoupled). The time series demonstrates that a number of “cold event” errors are not present in the coupled model. These events occur during periods of variable ice cover (storm events), in which errors in surface fluxes can result in 5-10^{o}C cold biases in the uncoupled forecasts.

Sub-arctic regions are especially rich with water bodies, both lakes and rivers. The effect of lakes with long ice cover period needs to be realistically reproduced in forecast models. Rivers demonstrate a different thermodynamic regime with a shorter ice period with consequences to surface-atmosphere energy/momentum exchange. River runoff formation in the Arctic is strongly regulated by the permafrost presence in the soil. Moreover, river runoff (i.e., by Siberian rivers Ob, Yenisei and Lena and Mackenzie in Canada) inputs large volumes of freshwater and solutes/particulate matter to Arctic ocean favouring the ice growth and influencing the ocean circulation (*Wu 2008*).

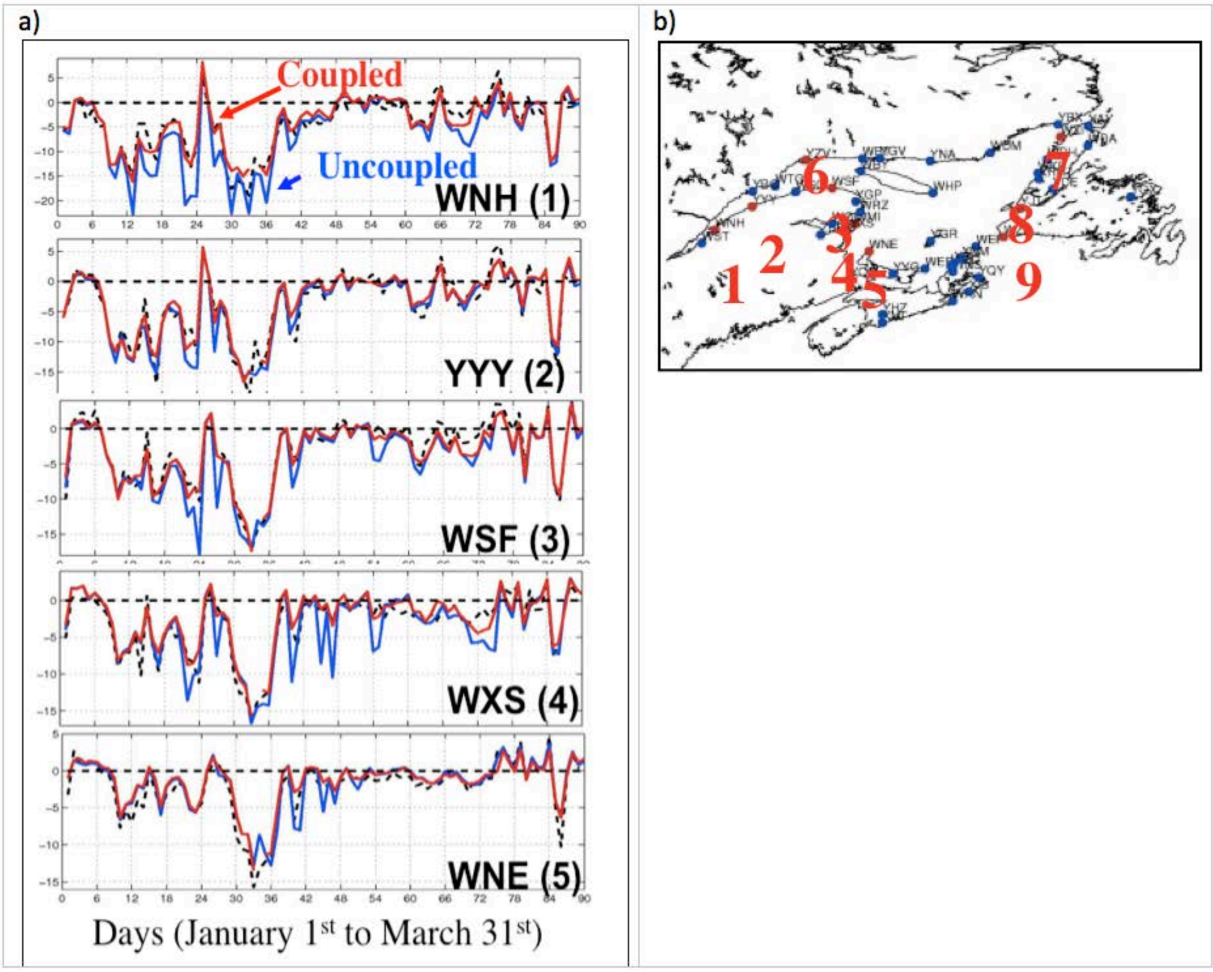

Figure 16 - Time series of 24-hour 2-metre temperature forecasts (a) from uncoupled (blue) and coupled modelling systems (red) compared to observations (black) for selected stations (b) in January 2010

For longer time scales, the larger scale ocean circulation and sea-ice dynamics become increasingly important. Polar oceans are often stably stratified with colder and fresher water above the warmer and saline water transported below, vertical mixing in these conditions is not well represented in models and also calls for fine vertical resolution. The baroclinic Rossby radius in the ocean is about 5 km; the ocean model should have a horizontal resolution of about 1 km, which is large enough to be sure the hydrostatic approximation is still valid. A fine horizontal resolution in ocean models is also required to adequately represent flow through small straits (e.g., in the Canadian Arctic Archipelago) and tidal flows. Inclusion of tides in ocean models is needed as they affect ice motion and deformation, and generate large vertical heat fluxes that can lead to the formation of polynyas (e.g., *Saucier et al. 2004*) as well as affect the evolution of ice thickness on longer timescales.

High resolution is especially important for sea ice forecasting. Sea ice exhibits large spatial variability on sub-kilometric scales, such as leads, which as noted above can lead to strongly non-linear exchanges of heat and moisture with the atmosphere affecting weather forecasts. Moreover, it is often these small scale features that are of most interest to direct users of sea ice forecasts (e.g., coast guard, search and rescue, shipping). To adequately simulate leads as well as pressure ridge formation, it is crucial that rheology, i.e., the relationship between applied stresses and deformations is correctly formulated. However, the widely used Viscous-Plastic (VP) (and related Elastic-Viscous-Plastic) rheology is contentious. Indeed, the VP rheology underestimates sea ice deformations (*Kwok et al. 2008*), the simulated shear lines are too broad and do not significantly refine as the spatial resolution is increased (*Wang and Wang 2009*), and statistics of deformations do not match observations (*Girard et al. 2009*). Additionally, landfast ice and ice arching are poorly represented in most sea ice models (*Dumont et al. 2009*).

The increase of horizontal resolution of global atmospheric models up to 1-5 km is necessary for better representation of steep orography in some parts of Arctic and Antarctic. This will inevitably require global non-hydrostatic models. Some centres already have experimental versions of such models; others are developing them. Global non-hydrostatic models are very demanding in terms of computational resources, especially in spectral models, so it is important that they use massively-parallel computer systems efficiently. Still, there is the so called 'grey zone' problem with models having a resolution (1-5 km) for which the convection process is partly but not fully resolved by the model. With even finer resolution (1 km or less) there are further problems with the boundary layer parameterization, since turbulence may also become partly resolved.

4.3 Key Challenges

- Improved parameterization of the atmospheric boundary layer is essential. Polar boundary layers are often stable, or strongly stable, and stable boundary layers are not well represented by current parameterizations. A number of new or improved theoretical frameworks focusing on the SBL have been developed over recent years (e.g., *Sorbjan 2010, Mauritsen et al. 2007*, etc.). Some of these theoretical frameworks have been tested against observations with some positive results, although further testing is certainly warranted.
- Vertical resolution is often insufficient in the boundary layer, especially for SBL conditions. This leads to problems both in the boundary-layer and, in the proximity to complex or steep topography, in the free atmosphere when elevated strong temperature inversions are not represented (e.g., *Petersen et al. 2009*).
- Horizontal resolution with highly heterogeneous surfaces such as marginal ice zones or complex often steep topography (e.g., coasts of Greenland, Canadian Arctic Archipelago or Antarctic Peninsula) presents a limiting factor. It is probably the case that we know the physics and parameterizations required to represent boundary-layer processes for many of these situations, but cannot implement them for operational forecasting or climate prediction because of resource limitations.
- Cloud microphysical processes in models are often independent of aerosol and chemical variables, e.g. particle size distributions are constant. There is increasing evidence that this should not be the case, and that aerosol concentrations are a primary factor in cloud microphysical processes.
- A high-resolution sea ice model including formation and evolution of polynyas and ice leads (important for all ranges, from short-range to seasonal)
- Representation of thermodynamic regime of lakes and their interaction with the atmosphere in permafrost zone including dates of ice cover setup and break-up (important for all ranges, from short-range to seasonal).
- Explicit simulation of river flow dynamics and thermodynamics, runoff and ice cover setup and break-up dates based on sophisticated formulations. Adequate representation of permafrost in the soil and its effect on runoff formation (this is important for intraseasonal and seasonal forecasts)

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5. DATA ASSIMILATION

5.1 Background

The efficiency of data assimilation to provide an accurate estimate of the current state of the system depends equally on the performance of the numerical model, of the data assimilation framework and the employed observations. As in other regions, advances in data assimilation over polar regions therefore always require combined development in these three areas.

Current *global* operational systems are mostly based on incremental 4D-variational algorithms to trade off computational efficiency and medium-range forecast performance. Forecast (and in the case of incremental 4D-Var outer loop) resolution ranges from 15 to 50 km and inner loop resolutions are about a factor of 5 coarser. The models are mostly based on hydrostatic dynamical cores.

There are fewer *regional* operational systems covering polar areas and they can exhibit more variety in terms of model and data assimilation system types, also because these systems aim at skill over smaller areas and shorter forecast time ranges. Locally, large orographic variability also exists in polar areas which may be important to resolve to properly represent its impact on the large scale (e.g., orographically forced gravity waves; *Rabier et al. 2010*). One particular aspect of polar regions (compared to the mid-latitudes) is that longer planetary waves are of less prominent impact. Furthermore, synoptic-scale systems have smaller spatial scales than their mid-latitude counterparts due to a decrease of the Rossby radius of deformation (*Jung et al. 2006*). This will have implications on the requirements for model resolution, particularly in the inner-loops of the minimization.

Experience from observing system experiments, also employing data from targeted observation campaigns, and advanced analysis/forecast diagnostics suggest that those areas, in which accurate initial conditions are most important for forecasting, are often cloud covered and thus less accessible to satellite observations and not necessarily near conventional observation networks (THORPEX DAOS; *Majumdar et al. 2011*). Further, data assimilation systems only start becoming more flexible in defining weather-state dependent background errors and therefore assigning larger weights to observations in areas where model uncertainty is large. This situation is generally more serious at high latitudes since there may be less reliable observations in those areas. Background error covariance statistics are mostly globally defined and therefore dominated by mid-latitudes and the tropics.

Figure 17 demonstrates the lack of ensemble spread over polar sea ice noting that the spread is mostly generated by perturbing observed SST, perturbing all assimilated observations and by stochastic formulations of physical parameterizations. Consequently, analysis increments are small, particularly in the lower troposphere. In turn, areas with large increments (over the US, Europe, parts of Asia) identify locations of dense observational networks. Note that the stochastic physics (*Palmer et al. 2009*) have been mostly devised for tropical latitudes and thus cannot be expected to correctly represent model error at high latitudes.

Most short- and medium-range systems are uncoupled and thus surface constraints (sea-state, sea-ice, land surface) at initial time are provided from observational and/or climatological information that are evolved through different approaches (e.g., constant, persisted anomalies, seasonal, etc.) into the forecast range. At present, snow and sea-ice models are significantly less sophisticated in global systems than ocean, wave and land surface models – lakes and rivers are mostly unresolved.

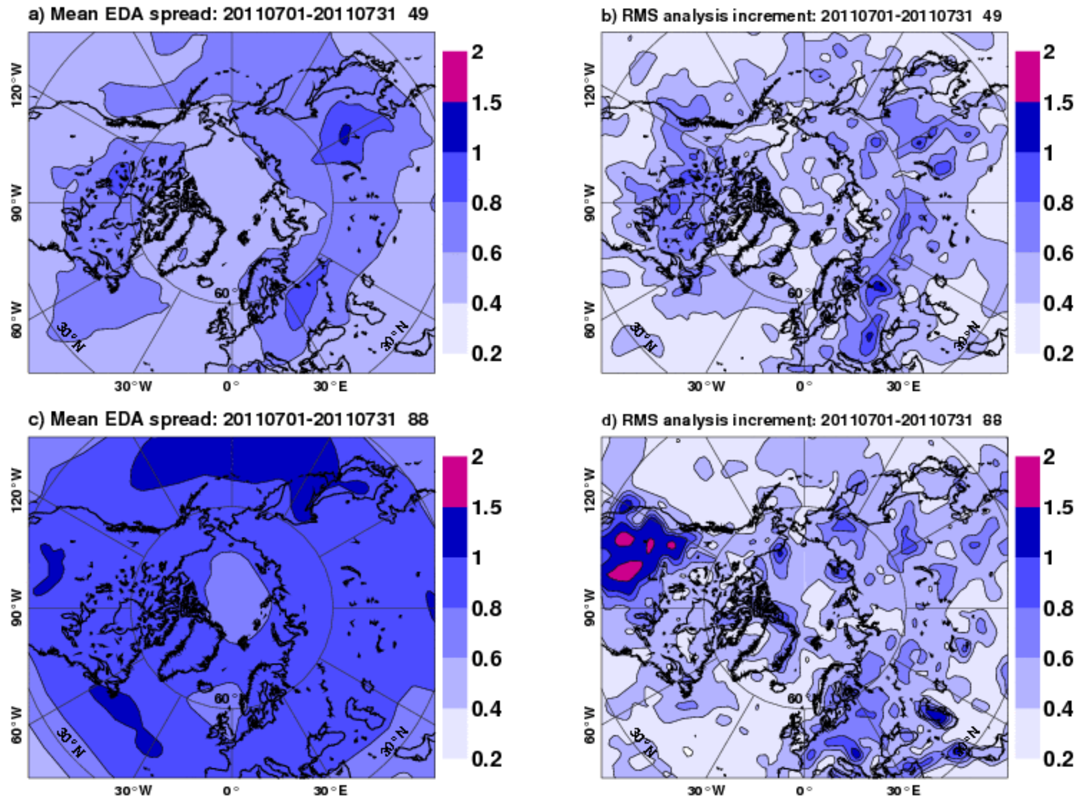

Figure 17 - Mean ECMWF ensemble short-range forecast spread (a, c) and root-mean-square analysis increments (b, d) for temperature (in K) in July 2011 at 200 hPa (top) and 1000 hPa (bottom) over the Arctic

Ensemble-based forecasting systems employ the same analysis techniques that are used for single deterministic forecast initialization but the members are initialized by an ensemble of analyses. Ensemble analysis members can be generated by running several (e.g., 4D-variational) data assimilations in parallel which contain different realizations of observation and model errors such that the analysis spread corresponds as closely as possible to the analysis error. Since variational data assimilation also requires the definition of observation and model error characteristics, recent developments have lead to combined ensemble-variational set-ups which produce state dependent model error covariances for 4D-Var and the analysis uncertainties for ensemble forecast initialization at the same time. In the future, this evolution is expected to produce even more seamless ensemble-based analysis and forecast system. The much smaller dimension of the inversion problem in regional systems allows the use of ensemble Kalman filters that are purely based on forward modelling for both the model's state and the error covariances. In the future, these filters may become competitive on a global scale.

A particular problem with polar data assimilation is the general lack of conventional (i.e., non-satellite) and the under-exploitation of satellite observations. Conventional observations are usually present near inhabited areas along coastlines and from a few dedicated observatories. Data from field experiments are often retained by the participating teams for significant periods and not in a format that is easily ingestible by operational centres. This restricts their usage to verification rather than operational assimilation.

Satellite observation usage at high latitudes is limited by: (1) difficulties in characterizing surface reflection/emission (snow, ice) in radiative transfer calculations, (2) shallow and nearly isothermal tropospheres reducing the vertical sounding capabilities and the detection/treatment of clouds that are present over long periods in polar areas, (3) distinct model biases (clouds, surface, PBL) causing observation rejection in case of too large discrepancies from the model. In addition, variational bias correction of (satellite) observations is vulnerable in areas with few anchoring (conventional) observations and is prone to absorbing model rather than observation biases.

The above issues add up in the lower polar atmosphere so that the analyses at these levels are mostly driven by the model and much less by observations. This causes two main problems. Firstly, forecast verification with analyses that is common practice becomes much less useful because it degrades to a model-with-model comparison (e.g., see Figure 3). Verification is thus focused on lower latitudes causing model improvements to be tuned to lower latitudes as well. Secondly, the above mentioned need for a characterization of observation and model errors for variational and ensemble systems can collapse in areas that are underconstrained by observations: In the absence of observations and a lack of spread from model error simulation the analysis uncertainty will be largely underestimated. This will give even less weight to sparse observations in successive cycling and the analyses and forecasts will be again mostly model driven. In addition, much of the vertical distribution of analysis increments is driven by background error structure functions. These are not well defined for polar areas, are likely to be quite different from middle and lower latitudes, and do not produce sufficiently accurate vertical localisation in shallow atmospheres.

Irvine et al. (2011) provides an example of the problems of polar data assimilation, from the Greenland Flow Distortion Experiment. When data from dropsondes from coastal Greenland were included, they degraded the model forecast, as they spread inappropriate conditions up model levels over Greenland and these then propagated downstream over Scandinavia. The same paper also showed, albeit for one case only, that if the error covariances for dropsonde observations were reduced, then significant (20%) improvements in forecast could be achieved.

Figure 18 shows an example of the strong impact in the ECMWF model of the Concordiasi drifting gondola at cruise level 70 hPa and of dropsondes on temperature in the lower troposphere where only few observations are available from operational networks and satellite data. Initial model-sonde intercomparisons confirm the lack of representing lower tropospheric temperature inversions over cold surfaces, in particular over the Antarctic plateau (*Rabier et al. 2012*).

Figure 19 illustrates the often significant differences of mean analysis states for key parameters between the operational weather forecasting systems. These are due to differences in data assimilation systems, forecast models, actively assimilated observing systems, short-range forecast error formulations etc. For most parameters the differences are particularly large over polar areas and high-altitude terrain.

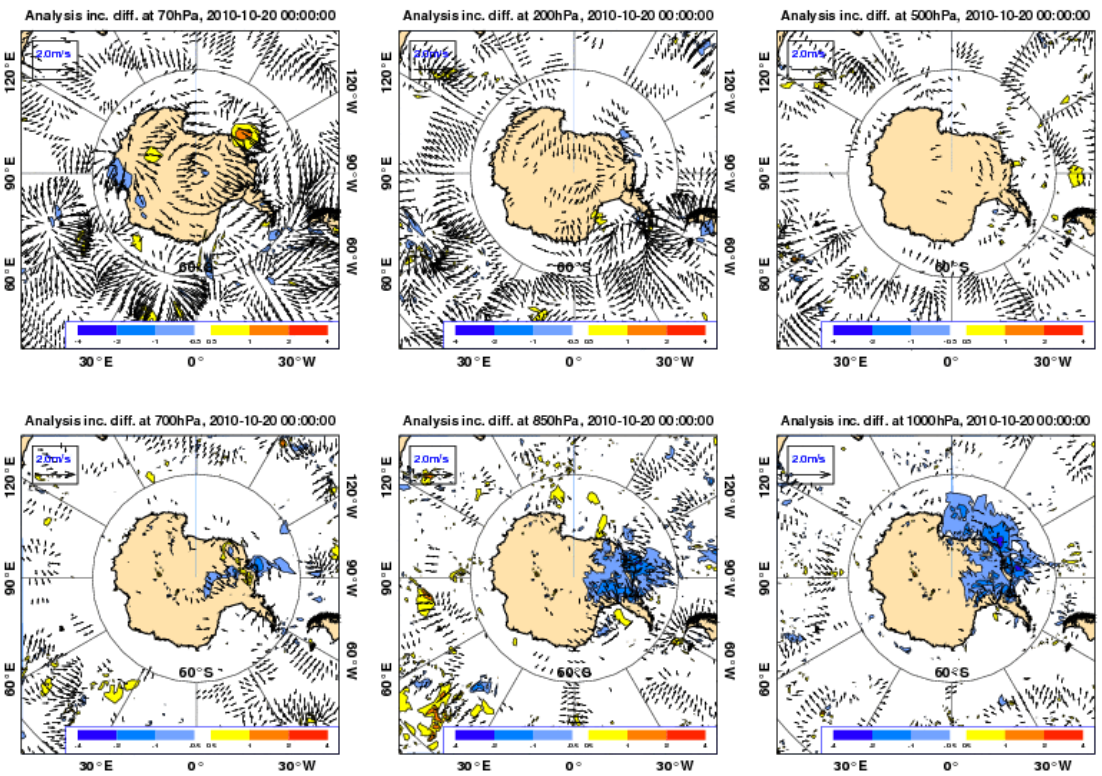

Figure 18 - Difference of temperature (colour) and wind (arrows) increments between analysis runs with and without assimilating Concordiasi gondola/dropsonde observations. Panels show results at 70, 200, 500, 700, 850, 1000 hPa on 20 October 2010 (top left to bottom right)

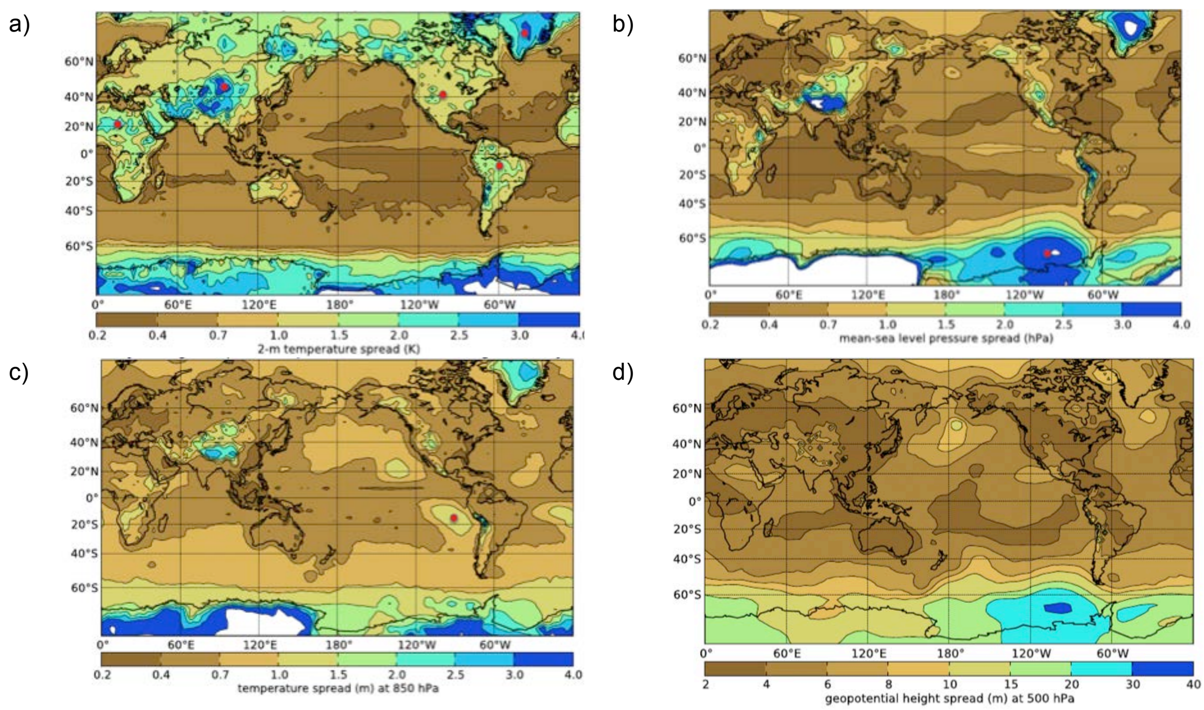

Figure 19 - Spread of analysis mean for (a) 2-metre temperature, (b) mean sea-level pressure, (c) 850 hPa temperature, and (d) 500 hPa geopotential height from 5 operational TIGGE models (UKMO ECMWF, NCEP, CMC, CMA; 10/2010-11/2010) (*Hamill 2012*, pers. comm.)

5.2 Key Challenges

The key scientific challenges highlight the need for joint developments in numerical model, data assimilation system and observational data usage:

- Parameterizations for sub grid-scale processes (see also Section 4), i.e., clouds, radiation, boundary layer, surface (noting that these parameterizations need to perform at global scale) need to be improved with focus on:
  - Mixed phase clouds, cloud aerosol interaction, lower level humidity
  - Stable boundary layers, interaction with clouds, orographic drag
  - Snow covered surfaces, snowmelt, snow on sea-ice, frozen surfaces.
- The availability of lower tropospheric and surface observations over sea-ice, Greenland and the Antarctic continent is limited. There are drifting buoys over the Arctic Ocean, and arrays of automatic weather stations, as well as ground-based GPS over Greenland and Antarctica, but their sparseness is not sufficient to characterize weather over polar areas. These observations are crucial for verification and data assimilation, and their sensitivity to parameters linked to the above physical processes is important.
- The characterization of model errors (random and systematic, error standard deviations and structure functions) and the capability of model error formulations for ensemble data assimilation and ensemble prediction representative of polar weather is required. In this context, an evaluation of the value of ensemble based systems at high latitudes is needed. Among others, the impact of ensemble size (sampling error), the methodologies for representing model and observation uncertainty, the impact of lateral boundary conditions for regional systems (particularly over the Southern polar region), given sparse observational data are important.
- The potential of coupled (ocean, sea-ice, rivers, lakes) dynamic modelling and coupled data assimilation for short and medium ranges needs investigation. Coupling issues and process speed / scale mismatch require attention.
- The characterization of lower latitude weather sensitivity to polar areas and thus the benefit of accurate analyses in polar areas for mid-latitude forecast skill needs attention. A focus could be put on, e.g., polar lows, sudden stratospheric warming events? Sensitivity studies should also include observing system experiments withdrawing key observations in polar areas.
- Tools for testing model formulation and data assimilation systems (error formulations), for optimizing observational impact and verification are:
  - Testbeds (parameterizations, data assimilation, coupling, resolution (model, minimization), observations etc.)
  - Adjoint diagnostics of the short-range forecast impact of observations, model and observation/model errors with polar energy norms, complemented by OSEs (short-medium range)
  - Polar region specific verification metrics (see also Section 2) for deterministic and ensemble forecasting systems.

6. ENSEMBLE FORECASTING

6.1 Background

Most operational weather and climate prediction centres run ensemble forecast systems. In doing so, they recognise that predicting the uncertainty in prognostic variables such as temperature, precipitation or wind speed is central for robust decision making across a range of weather and climate forecast applications. Sources of forecast uncertainty include limitations on the accuracy and representativity of observations, on the methods by which these observations are assimilated into forecast models, and on the forecast models themselves. Dynamical instabilities in the climate system makes dynamical weather and climate forecasting critically sensitive to uncertainty in both the initial state and the model used for advancing information in time. However, there is very little information on the way current methodologies used to address initial-condition and model uncertainty perform for predictions over polar areas. The performance observed over tropical and mid-latitude regions should not be automatically extrapolated to polar regions because most of these techniques have been developed taking into account the specific characteristics of the climate system over the former regions.

The non-linear nature of the climate system makes dynamical weather and climate forecasts sensitive to uncertainty in both the initial state and the model used for their formulation (*Palmer, 2001*). In other words, the main uncertainties at the source of forecast error are of two types:

- Uncertainties in the initial conditions, which are accounted for by generating an ensemble from slightly different atmospheric and ocean analysed states (*Wang et al. 2010; Stockdale et al. 2011*). Due to non-linear processes such as advection by atmospheric flows - the unstable growth of uncertainties may, in principle and in practice, depend on the actual state (*Palmer, 2001*). In other words, reliable predictions are not obtained by assuming the same standard uncertainty development for all forecasts, but must be estimated uniquely for each forecast. The perturbations of the initial conditions can be either of an optimal statistical nature (*Tang et al. 2005*) or based on insight into the dynamics of the physical system (*Balmaseda et al. 2008*).
- Uncertainty in model formulation, due to the inability of dynamical models of climate to replicate every single aspect of the climate system with arbitrary detail and the approximations used in dynamical cores (*Palmer, 2001*). Climate models have limited spatial and temporal resolution, so that physical processes that are active at smaller scales (convection, orographic wave drag, cloud physics, turbulent mixing, etc.) must be parametrised using semi-empirical relationships and the continuous equations that describe the physical system have to be discretized, which entails arbitrary choices and broad approximations. Some physical processes are also too computationally expensive to calculate them without approximations (e.g., radiation) or are inadequately known (e.g., cloud microphysics). Included in this category there are also uncertainties originating from changes in the external forcing.

As a consequence of these uncertainties, forecasts have errors due to the inherent dynamical instabilities that make initial errors to grow with forecast time. In this context, an individual forecast is of limited value since it cannot represent an estimate of the error along with the forecast. Instead, sets of forecasts are carried out to predict the range of possible evolutions of weather and climate and take proper account of as many sources of uncertainty as possible. This is known as the ensemble method. Operational weather prediction for the medium and extended range is nowadays unimaginable without ensemble prediction systems (EPS). Climate projections for given external forcing developments are also using ensemble methods to account for uncertain information. Forecasting over the short (up to 3 days) and very short (up to 24 hours) ranges does still not use EPS to the same extent, although that is changing quite fast. By employing EPS for weather forecasting and climate projections, it is recognized that predicting the uncertainty in prognostic variables such as temperature, precipitation, wind speed and so on, is central for robust decision making when weather and climate information are crucial. Here we consider systems for weather prediction, in which both accurate initial states and adequacy of the prediction method (i.e., the forecast system) are crucial, and not climate projections.

Several forecast ranges can be considered in the ensemble forecasting context. The short range covers forecasts of up to three days. Short-range forecasts would reliably include addressing sub-synoptic scale weather features with considerable information sharpness. Probability forecasts for high-impact weather should normally condition immediate protective actions over well-defined regions. In polar areas, this would include polar lows (*Rasmussen and Turner 2003*) and other perturbations over open oceans, phenomena associated with Arctic fronts and the ice-edge (e.g., *Grønås and Skeie, 1999; Drüe and Heinemann, 2001*), and low-level winds generated by flow over and around orography in stably stratified conditions (e.g., *Skeie and Grønås, 2000; Renfrew et al. 2009b*). The papers by *Renfrew et al. (2008)* and *Kristjánsson et al. (2011)* give a thorough overview based on unprecedented observations and model studies.

Uncertainty information in medium-range forecasts (from three up to 15 days) is relevant to in-situ preparedness. In polar areas, synoptic and planetary-scale flow patterns pre-conditioning high-impact weather are of particular concern, such as patterns associated with outbreaks of cold air over ice-free sea-surface in winter which enable lower-boundary forcing by huge fluxes of sensible and latent heat. Such situations should be predictable in the medium range and allow the development of early warning systems. Ensemble information from sites such as http://tparc.mri-jma.go.jp/TIGGE/tigge_extreme_prob.html which make use of TIGGE data provide an excellent proof of concept of the value of such probabilistic information. For example, Figure 20 shows a high likelihood of very strong surface winds in the Ross Sea five days in advance.

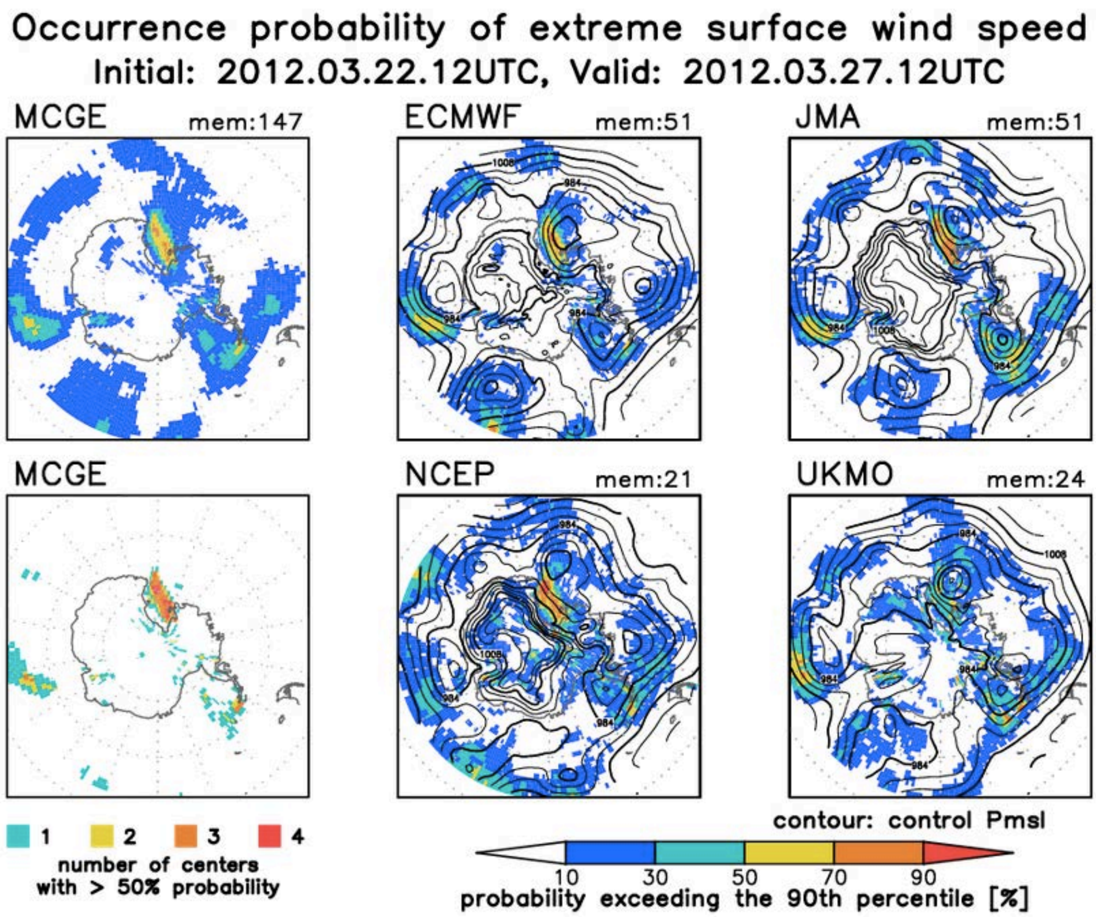

Figure 20 - Example of probabilistic forecast information - the likelihood of extreme surface winds - based on TIGGE ensemble model data (from http://tparc.mri-jma.go.jp/TIGGE/tigge_extreme_prob.html)

Prediction of individual polar lows, or similar upscale organised disturbances, relies, however, on accurate initial analyses of upper-level potential-vorticity anomalies and the correct representation of the upscale organization of the deep convection (*Kolstad, 2011*). Unfortunately, the latter is hardly predictable beyond the short range.

The sub-seasonal range includes forecasts of up to 45 days and has applications in many different socio-economic fields. For instance, Arctic populations, whose livelihoods depend on fishing and hunting (*Fox, 2003*), could benefit from such predictions, through a better organisation of ship supplies, fishing activities or the development of polar ecotourism. Extended-range forecasts include sub-seasonal to multi-annual time scales and are important for assessing marine access to the remote polar regions (Arctic Climate Impact Assessment 2004). This access is highly variable and these variations can incur considerable logistical challenges, with substantial associated costs, for things like re-supply efforts and scientific accessibility.

There is a critical need for reliable probabilistic predictions, with quantified uncertainty for Arctic and Antarctic conditions at all forecast ranges. This need is likely to increase as changes in the polar regions enhance marine accessibility but also make the weather more variable and the polar environment subject to changes in extreme events.

6.2 Initial-Condition Uncertainty: Ensembles

One of the key aspects that ensemble prediction systems need to simulate to provide accurate probabilistic predictions is the effect of initial uncertainties on forecast error. These uncertainties have been simulated with, e.g., atmospheric singular vectors (SVs), which are the perturbations characterized by the fastest growth (*Buizza and Palmer, 1995*) over a finite time interval. At ECMWF different sets of SVs were used to better sample the initial uncertainties. Initial-time SVs growing into the first 48 hours of the forecast range, which represent uncertainties growing during the forecast time, were mixed with evolved SVs computed to grow during the 48 hours leading to the analysis time, which represent uncertainties that have been growing during the current and past data-assimilation cycles. The initial-time and evolved SVs were scaled to have an amplitude comparable to the analysis error estimate provided by the ECMWF data assimilation system (*Barkmeijer et al. 1999*). However, the focus of operational SV-based methods is on the main storm track regions (baroclinic instability) in the mid-latitudes.

None of these SV-based methods targets specifically the polar regions. One reason for this is the choice of a norm which leads to SVs that maximise the total energy. Another reason is their relatively coarse resolution (triangular truncation T42), and a third reason is their (almost) adiabatic development. These choices lead to a natural selection of mid-latitude cyclone waves associated with combined baroclinic and barotropic instability. Such instabilities may partly explain the initial triggering of disturbances such as polar lows, but the mechanisms responsible for their further growth are considerably more associated with diabatic processes and interactions with the upper levels of the ocean and the sea-ice (e.g., *Linders and Sætra 2010; Stappers and Barkmeijer 2011*). Recently, ensemble data assimilation (EDA) perturbations have replaced the evolved SVs in the ECMWF EPS (*Buizza et al. 2010*). In terms of forecast quality, the EDA-SV configuration has a higher skill than the earlier SV-based system everywhere, although specific assessments for the polar regions are not available.

An alternative for the initialisation used at NCEP is the Ensemble Transform and Rescaling (ETR)[5]. However, as at ECMWF, there is no sea-ice model coupled to the atmosphere in this system and no attempt to target the polar regions is made. Figure 21 shows an example of the ensemble forecasts that can be obtained with this methodology. The Arctic Oscillation (AO) has been linked to the Arctic climate variability and similar connections have been found for the Antarctic Oscillation (AAO) - e.g., *Guémas et al. (2009), Thompson and Wallace (2000), Thompson et al. (2000).*

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5 *http://www.emc.ncep.noaa.gov/GEFS/mconf.php*

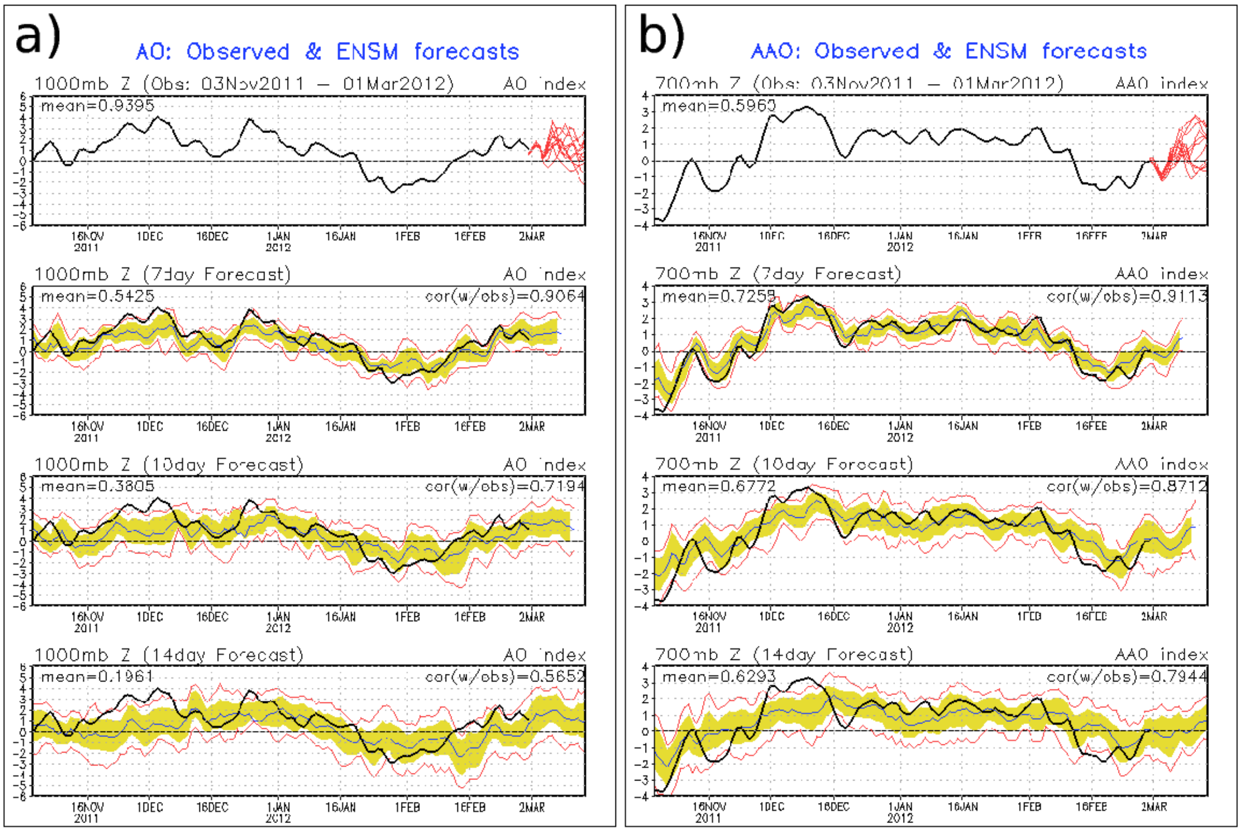

Figure 21 - Arctic (a) and Antarctic (b) Oscillation index predictions performed with NCEP's GFS. The first row shows the ensemble predictions made on 2 March 2012, along with the observations from 3 November 2011 to the 1 March 2012. The other rows show the ensemble range (red lines), ensemble interquartile range (yellow shade) and ensemble mean (blue line) for the seven-, ten- and 14-day forecasts. The ensemble-mean correlation with the reference (NCEP analysis) is shown in the upper right corner of each panel

For time scales longer than a few days, both the ocean and the sea ice have to be initialised. In the Arctic, this may even be the case for short-range prediction, as interactions between upper level ocean mixing, sea ice and snow cover may contribute considerably to the rapid growth of atmospheric disturbances. According to *Alexander et al. (2004),* local anomalies in sea-ice concentration create anomalies in ocean-atmosphere surface heat fluxes of very small spatial extent but very large amplitude. If the sea-ice concentration anomalies are collocated with the local storm track, as occurs in the Greenland Sea, the intensity and path of the storm track can be directly affected. Hence, sea-ice initial-condition uncertainty has to be appropriately sampled when creating the ensemble. In a forecast system based on an Earth System Model, all components need to be initialised. While operational reanalysis (e.g., *Saha et al. 2010*) are used for the ocean and the atmosphere, the sea ice suffers not only from the scarcity of ice thickness observations, but also from the lack of quasi-operational analyses and initial-condition estimates that can be used to initialize the ensembles. Figure 22 shows how different sea-ice reanalysis can be, and how they can differ from the different available observational datasets. For instance, in NCEP's operational sub-seasonal forecast system[6] only the sea-ice extent is used in the initial conditions, although some initial-condition uncertainty is sampled with the lagged initialisation method employed, where predictions are initialised with six-hourly intervals.

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[6] *http://origin.cpc.ncep.noaa.gov/products/people/wwang/cfsv2fcst/*

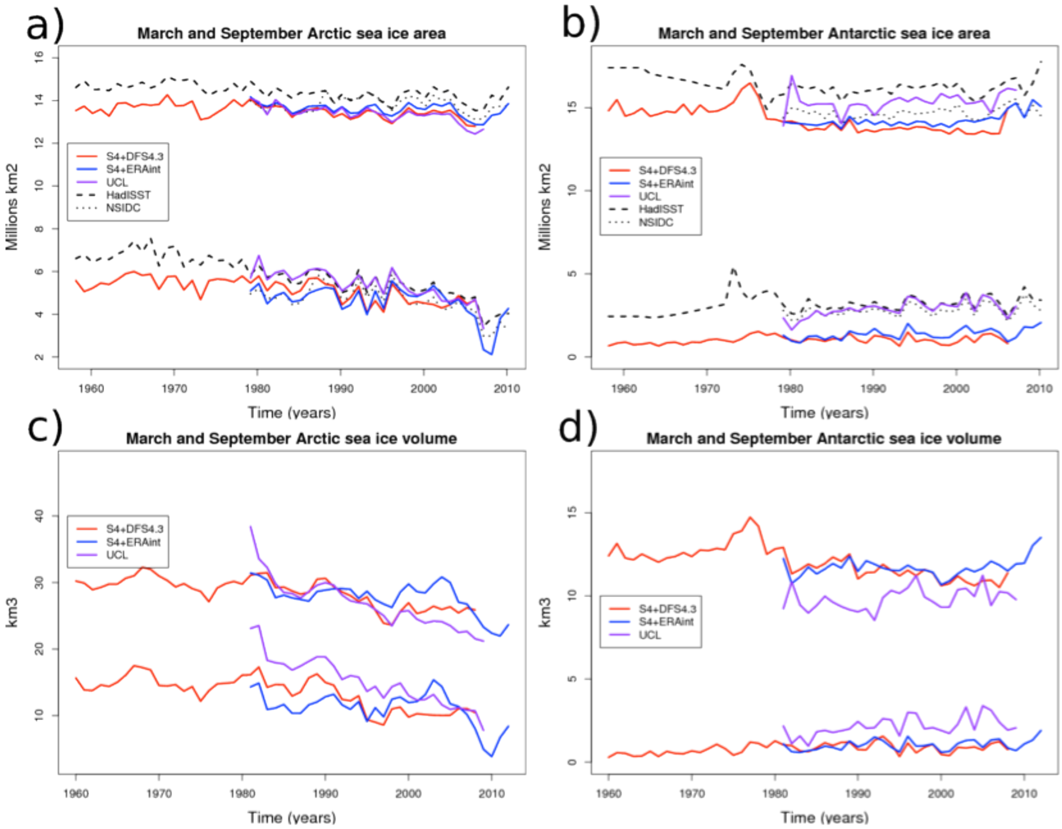


Figure 22 - Sea-ice area (panels a and b) and volume (panels c and d) for three different reanalyses over the Arctic (panels a and c) and the Antarctic (panels b and d). For the sea-ice area, the HadISST and NSIDC data are used as reference. No long-term observational dataset is available for the sea-ice volume

Johnson et al. (2012) show the large uncertainty present in coupled ice-ocean model simulations of the Arctic as compared to available satellite and in situ observations of ice thickness (see Figure 23). In particular, they find a tendency for ice-ocean models to overestimate thin ice (<2m) thicknesses and underestimate the thickness of thick ice (>2m). It is suggested that errors in thin ice are related to excessive ridging of newly formed fast ice. This is of particular concern for polar prediction as it implies a significant reduction of atmosphere-ocean heat fluxes during periods of rapid seasonal transition.

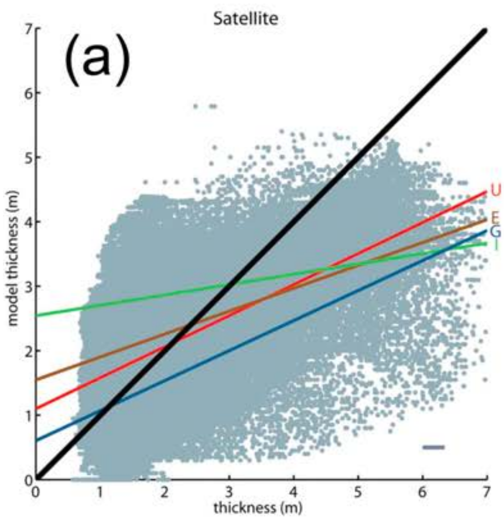


Figure 23 - Linear fit between observed and model thickness from satellites. The axis limit is set from the maximum observed. The first letter of each model is noted in the upper right by the regression line. (From *Johnson et al. 2012*)

Those systems without a dynamic sea-ice model use in practice a prediction of sea ice concentration during the forecast. However, sea ice is also a variable subject to forecast errors. The first attempts at producing sea-ice climate predictions have relied on statistical methods (*Drobot et al. 2006; Lindsay et al. 2008*). However, with rapid changes occurring in the Arctic climate, the relations between the sea-ice variables and their predictors do not hold (*Holland and Stroeve, 2011*); hence the need for dynamical forecast systems. Extreme sea-ice conditions such as a summer ice-free Arctic Ocean expected to occur during the twenty-first century - perhaps within a decade or two - have recently raised attention. According to the pioneering study by *Tietsche et al. (2011),* the sea-ice cover would recover in approximately two years, mainly through heat exchanges with the overlying atmosphere. The skill associated with this persistent behaviour encourages the correct initialisation of the sea ice, always using the ensemble method to address the uncertainty in sea-ice initial conditions, which should also address the issue of model inadequacy due to the relevance of the sea-ice, atmosphere and ocean interactions that are not properly represented in current forecast systems. Figure 24 illustrates the current ability to predict the sea-ice extent at seasonal time scales (*Wang et al. 2012*).

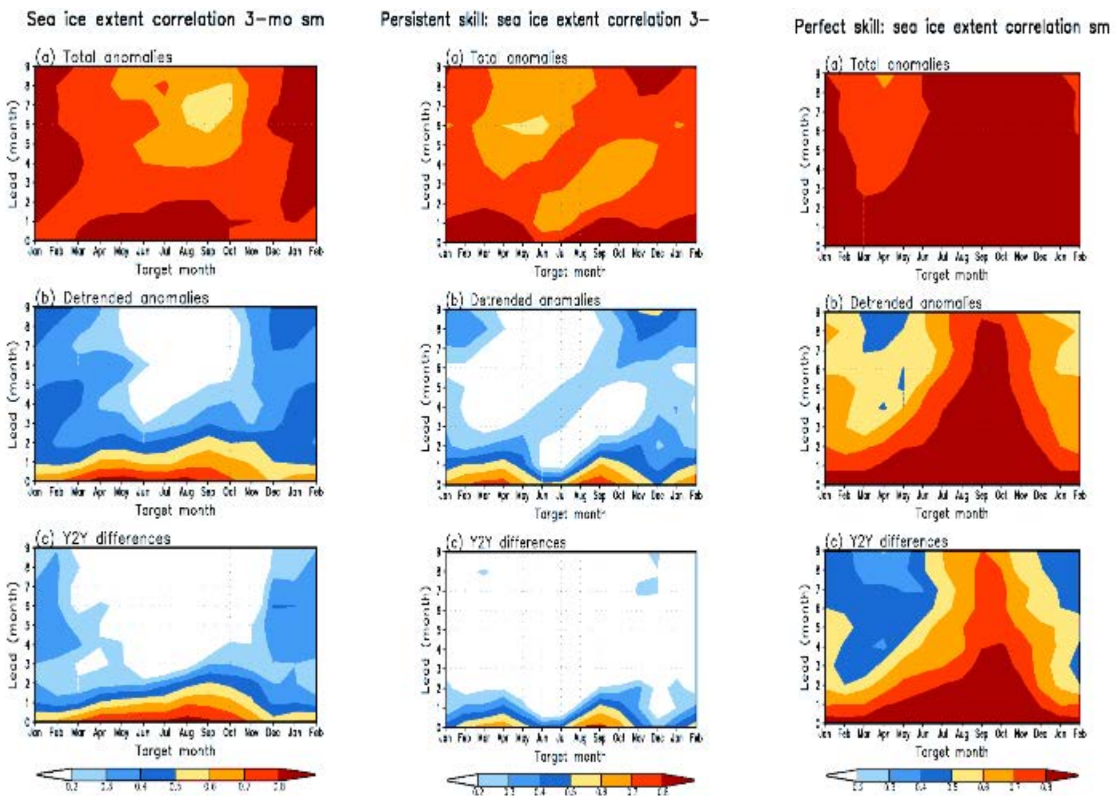


Figure 24 - Left column: Sea-ice extent anomaly correlation between observations and CFSv2 forecasts (1981-2010) as a function of target time (horizontal axis) and lead time (vertical axis) for a) anomalies, b) detrended anomalies and c) year-to-year changes. Central column: The same for a simple persistence model. Right column: The same using the perfect model approach (correlation of each ensemble member with the ensemble mean). From *Wang et al. (2012)*

6.3 Model Inadequacy: Multi-Model, Perturbed-Parameter and Stochastic Physics

The ensemble method attempts to deal with uncertainties in the initial condition, while several methods to address model uncertainty have been proposed (*Palmer 2001*):

- The multi-model method empirically samples errors that occur due to structural inadequacy in individual climate models by using models with different formulations and parametrization. This approach relies on the fact that global climate models have been developed somewhat independently at different climate institutes, using different numerical schemes to represent the dynamics and applying different parametrization of physical processes. This is a simple, ad-hoc method that does not sample all the possible uncertainties such as those at the origin of the misrepresentation of the Euro-Atlantic atmospheric blocking. Examples for the short-range (GLAMEPS; *Iversen et al. 2011*), medium-range (TIGGE; *Bougeault et al. 2010*) and seasonal (DEMETER; *Palmer et al. 2004; Hagedorn et al. 2005*) time scales exist. *Doblas-Reyes et al. (2005), Weigel et al. (2008), Weigel and Bowler (2009), Iversen et al. (2011) and Hagedorn et al. (2012)* provide an excellent explanation to understand why the multi-model approach improves, on average, with respect to the best single forecast system in a probabilistic context.

- Given that some of the most important model uncertainties are in the specification of the parameters that are used in the physical parameterizations (*Murphy et al. 2004*), the perturbed-parameter approach samples model uncertainty by creating ensembles of alternative variants of a single model in which multiple uncertain parameters are perturbed (*Collins et al. 2006).*
- The stochastic-physics approach break this into two parts: (1) stochastically perturbed process tendencies (*Buizza and Palmer, 1999*) and (2) backscatter-type schemes consider that processes taking place at unresolved scales are not adequately represented by the current parametrization because, among other things, with the use of bulk formulae they assume that there is an ensemble of sub-grid processes in quasi-equilibrium with the resolved-scale flow. The inherent uncertainties are associated with computational representations of the underlying partial differential equations that govern atmospheric motion. The basis for stochastic parametrization (*Palmer, 2001*) is that whilst these partial differential equations may themselves be deterministic, at the computational level, the equations of motion for weather are not deterministic. For example, the bulk-formula parametrization, largely based on the notion of ensembles of sub-grid processes in quasi-equilibrium with the grid scale flow, necessarily approximate sub-grid tendencies in a turbulent system like the atmosphere with its power-law energy spectrum. Hence, stochastic physics schemes look for stochastic representations of the computational equations of motion. In an ensemble forecast, different realisations of these stochastic representations are used to generate the “model error” component of ensemble dispersion. Palmer (2001) suggested that sub-grid processes could be represented by simplified non-linear stochastic-dynamic models as an alternative to the deterministic bulk-formula approach. *Shutts (2005)* and *Shutts and Palmer (2007)* showed that a cellular automaton scheme to introduce stochastic perturbations in the physical tendencies had a beneficial impact in a medium-range global forecast model, while *Jin et al. (2007*) employed a state-dependent stochastic multiplicative forcing to improve El Niño-Southern Oscillation (ENSO) simulations in a simplified model.

These three methods are, to a significant degree, complementary. They have been compared in a seasonal forecast context in *Doblas-Reyes et al. (2009)* and *Weisheimer et al. (2011)*. Only the multi-model approach samples structural parametrization uncertainties, whereas only the stochastic-physics approach samples uncertainties arising from the effects of unresolved sub-grid scale variability on the grid scale parametrization outputs. The perturbed-parameter approach samples a plausible range of sustained changes to the deterministic outputs of the parametrization that are not accounted for in the stochastic-physics approach, and only to a limited degree in the multi-model ensemble. Note also that the use of initial-condition ensembles with either the multi-model or the perturbed-parameter approaches provides ensembles of simulations that sample both sources of uncertainty. The stochastic-physics approach, instead, samples both sources when an initial-condition ensemble is run with a single-model version.

6.4 Regional Ensemble Forecast Systems

Regional models are employed over limited-area domains to issue predictions at higher resolution than those provided by global forecast systems. Their area-limited nature requires that prediction data are provided at the open lateral boundaries. These systems thus have an additional source of uncertainty that must be accounted for. Since the lateral boundary data necessarily have to be predictions described with coarser spatial resolution than in the regional system, the amplitude of this source of uncertainty grows with forecast lead time.

There is an additional uncertainty associated with the missing description of the smallest scales in the lateral boundary data. Therefore, the distance between the lateral boundaries and the central domain of forecast interest should be sufficiently long for the regional system to develop the finer-scale systems and their upscale influence over the forecast range. If this is not the case, the resulting forecast will to a considerable degree provide a dynamical interpretation of the large scale data with respect to the forcing by the fine scale ground surface. Provided there are predictable information in the large scale data, such dynamical downscaling may add predictable small scale features (*Boer, 1994; Simmons, 2006*).

There are only a few examples of operational, or routine experimental, productions of short-range EPS covering polar areas. Within the TIGGE-LAM no system covers any parts of Antarctica, and there are only four systems known to cover parts of the Arctic:

- NCEP's short-range ensemble forecast system (http://www.emc.ncep.noaa.gov/SREF), which covers parts of the United States (Alaska), parts of Siberia, the Bering Strait, and Canada. Separate Arctic verification is not available from the web-site, and the system is still experimental.
- The Canadian Meteorological Centre's REPS covers more than half of the Arctic on the western hemisphere, but presently with resolution comparable to global EPSs. There is no specific forecast verification for the Arctic (*M. Charron, R. Frenette and N. Gagnon*: First operational implementation of the regional Ensemble Prediction System, REPS 1.0.0).
- The NorLamEPS run since 2005 at the Norwegian Meteorological institute (*Frogner et al. 2006*), and was upgraded in connection with the IPY-THORPEX in February 2008 (*Aspelien et al. 2011*). The domain includes parts of the European-Atlantic sector of the Arctic where polar lows and other high-impact wind systems develop, using grid mesh width of 12 km. Separate probabilistic verification for sites north of 65ºN are available. The p rediction of two polar lows with this system are discussed in *Aspelien et al. (2011)* and in *Kristiansen et al. (2011)* using a 4 km version of the non-hydrostatic UK Met Office Unified Model to dynamically downscale NorLamEPS. One polar low is fairly well predicted from before it is recognizable in the initial analysis, while the other is completely missed only hours before its occurrence. An example of regional EPS output of precipitation probability from *Kristiansen et al. (2011)* is shown in Figure 25.

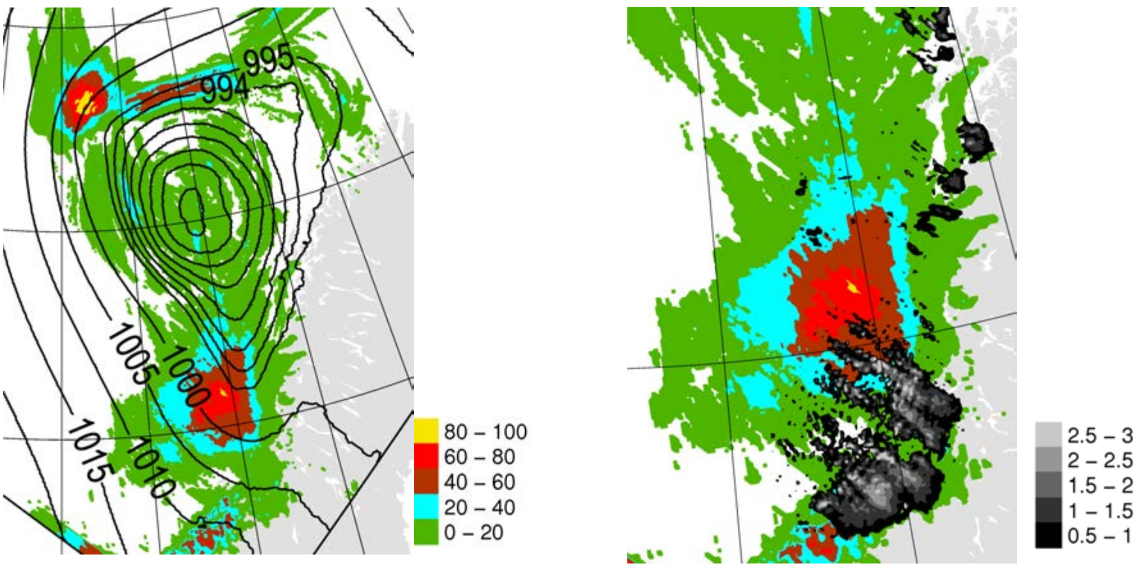


Figure 25 - Left: 3h precipitation from T+39-42h, valid 0900-1200 UTC 4 March 2008, from a met.no/Met office UK UM 4 km non-hydrostatic 20+1 member EPS. The colour legend shows the percent of members exceeding 2.5 mm/3h, and the isobars are ensemble MSL pressure for T+42h. Right: The precipitation probability overlain with radar observations as grey values, with the scale in units of mm/3h. From *Kristiansen et al. (2011)*

- The GLAMEPS (*Iversen et al. 2011*) has been run experimentally at ECMWF by the HIRLAM consortium together with the Belgian weather service since March 2011. The latest version of the system, which will be fully operational, is multi-model and multi-analysis, and runs in a domain that includes parts of the European-Atlantic sector of the Arctic with a resolution of around 11 km. Apart from using three separate initial analyses, there is no dedicated production of initial spread in the atmospheric state apart from the perturbations provided by the global EPS (from ECMWF).

6.5 Verifying Ensembles

Ensembles do not directly provide a probability forecast. Instead, a statistical model is necessary to transform the set of predictions given by the ensemble into a probability forecast. Ensemble forecasts have been widely used to issue probability forecasts (e.g., *Richardson 2001*), although they are not the only method available for this purpose (*Stephenson et al. 2005*). In the case of a dichotomous event, given an ensemble of simulations, a simple way of obtaining a probability forecast consists in computing the fraction of ensemble members for which the value of a given variable exceeds a threshold. More sophisticated methods of obtaining an estimate of the forecast probability distribution function (PDF) from the ensemble have been proposed (e.g., *Roulston and Smith 2003; Stephenson et al. 2005*), but given the limited sample size of long-range forecasts a simple, frequentist, non-parametric approach has been used.

Probability forecasts are verified in a special manner, attending to some forecast quality attributes that take into account the lack of determinism of the result. Verification examples of ensemble-based probability forecasts for the polar areas and their comparison with their deterministic counterpart are shown in Section 2, where the skill estimate measures the distance between the forecast probability density function and the verification reference. However, there is no systematic verification of the ensemble products over polar areas. Examples for winter medium-range EPS forecasts in the Arctic are described in *Jung and Leutbecher (2007).* However, other important aspects, such as the scale-dependence of the skill or the spread (*Jung and Leutbecher, 2008)* are still open.

Calibration and combination of ensemble forecasts is fast developing issue closely related to the forecast quality assessment. In short and medium-range prediction a reforecast set is not usually needed, although it has proven to be beneficial for robust forecast quality estimation and calibration of the ensemble, because model error is not dominant. However, for the sub-seasonal to seasonal ranges, model error is too large to be ignored. Therefore an extensive reforecast set spanning several years is needed to calculate model bias, evaluate skill and perform a robust calibration and combination of several forecast systems. Careful calibration and judicious combination of ensembles of forecasts from different models into a larger ensemble can give higher skill than that from any single model. Comparing, verifying and testing multi-model combinations from these forecasts, quantifying their uncertainty as well as the handling of such a massive dataset will nevertheless be challenging.

6.6 Predictability

In the ECHAM5/MPI-OM (*Roeckner et al. 2003; Marsland et al. 2003*) coupled climate model, the Arctic sea-ice thickness has been shown to be potentially predictable up to two years (*Koenigk and Mikolajewicz, 2009*). This estimate is computed from ensembles started from different January and July months of a 300-year pre-industrial control simulation. The ability of the coupled model to reproduce its own climate variability then provides a measure of potential predictability. This measure does not account for, on the one hand, the potential discrepancies between the observed and modelled mechanisms driving the sea ice cover variability and, on the other hand, the potential errors in the estimation of the initial observed sea ice cover state that could occur in a real prediction context. With the same methodology, *Holland et al. (2011)* obtained a longer predictability of the sea ice area with an above-average initial sea ice thickness than with an initial below-average one in the CCSM3 coupled climate model. Using a “perfect-model” approach, those studies aimed at assessing the predictability of the first kind of the sea-ice cover, i.e. the predictability of the internally-generated climate signal. Still in a perfect-model context, *Blanchard-Wrigglesworth et al. (2011*) estimate that the predictability of Arctic sea ice beyond three years is dominated by the external forcing rather than the initial conditions in the CCSM4 climate model (*Gent et al. 2011*).

6.7 Key Challenges

- Document initial-condition and model error characteristics. A catalogue of these errors for the different time scales and forecast systems (global, regional) will be necessary to foster the discussion about the methods to solve them.
- Comprehensively assess the benefits (particularly in terms of spread) of the different methods to deal with initial-condition and model uncertainties over the polar regions.
- Most methods to deal with initial-condition uncertainty have been designed using the experience over the mid-latitudes (like in the case of the SVs and EDA perturbations), but rarely taking into account the polar regions (shallow boundary layers, sharp land-sea contrasts). SV could be useful in the polar regions as long as baroclinic instability is involved (as it already happens in the Nordic Seas and close to the ice edge). SV-based studies with a focus on the polar regions should also include the effects of diabatic physics in the tangent-linear and adjoint models, as well as the inner product. SVs are not uniquely defined, and aspects like inner products or missing physical processes can influence the outcome. Besides, their pure focus on the atmosphere, and not on interactions with the ocean and sea-ice might lead to the underestimation of instability mechanisms causing strong weather impacts in the Arctic. The same is true to some degree for model uncertainty. For instance, model uncertainty associated with convection has been considered, but not over the polar regions. The impact of the_various schemes (multi-model, stochastic physics) should be assessed in the polar regions (e.g., not perturbing the lower latitudes during the integration).
- Documentation of all instability sources, which might contribute in different degrees to the spread growth.
- Development of initial-perturbation schemes for sea-ice and ocean specific for the polar prediction.
- Promote the discussion of the creation of sea-ice data assimilation and ensembles of sea-ice re-analyses.
- Development of schemes that account for model uncertainty (e.g., stochastic physics) in ocean, sea ice, land and river models.
- Determine mean spread-skill relationship (spread adequacy) for ensemble systems used for potential predictability studies (e.g., to assess to what degree are ensembles over-confident)
- Implement verification tools for ensemble forecasts for phenomena typical of the polar regions, with small scale and large observational uncertainty, such as the verification of the probability of predictions of polar lows. This includes assessing the spatial scales at which skill is maximum.
- Promote the inclusion of the polar regions in regional ensemble forecast systems, which systematically exclude most of the polar regions, even when running at low resolution.
- Increase skill over polar regions to levels currently reached in mid-latitudes. All dynamical and physical processes of relevance for polar prediction have to be validated in ensemble forecast systems at the short, medium-range, sub-seasonal and seasonal time scales. Appropriate sensitivity experiments have to be designed using also the ensemble methodology.
- A denser network of regular, in-situ observations and data-rescue efforts are needed to reduce initial-condition uncertainty.

- Foster the inclusion of chemistry, with its own issues linked to initialization and model inadequacy, into operational regional and global ensemble forecast systems.
- Perform reliable probabilistic predictions of extreme events at different time scales. This requires definitions of what extreme events are in polar regions.

7. PREDICTABILITY AND FORECAST ERROR DIAGNOSIS

7.1 Background

Predictability of weather is defined as the ability to reliably predict weather elements on specific sites at specific times with more information content than can be extracted from climate statistics for the same site and date. Weather predictability is limited by the notoriously unstable bio- thermo- and fluid-dynamical properties of ***the earth system*** of the atmosphere, the ocean with sea-ice, and the upper layers of the land surface. These instabilities lead to non-periodicity and sensitive dependence on the initial state (e.g. *Lorenz, 1963; 1969*) and strange attractors (*Ruelle and Takens, 1971*). Predictability is lost after a final lead time, the predictability limit, when prediction errors no longer grow with lead time and thus no qualified prediction is systematically better than any arbitrary climatic state.

The predictability limit is a consequence of the inherent instabilities leading to growth of perturbations, unavoidable uncertainties in initial state and boundary data, and the saturation level of prediction errors. Due to the non-linear nature of processes in the climate system, these three elements will depend on the actual state of the weather, the geographical area. Therefore, to forecast the predictability associated with a given prediction can yield valuable information for users. Furthermore the spatial scales are interlinked and the growth rates of errors associated with free flows increases with decreasing scales (*Lorenz, 1969; Leith, 1971*).

Since errors always will be saturated for the smallest scales, even a perfect large-scale initial state will become contaminated with errors after some hours. For near perfect prediction models, the accuracy of one-day forecasts will therefore determine an upper bound of the inherent predictability. As remote sensing technology develops and the methods to exploit such data in high-resolution data-assimilation improve, there are potentials for extending the upper bound of the predictability. Model imperfections associated with insufficient resolution and inaccurate representation of physical processes reduces the ability to realize this predictability in practice.

Experience from the ensemble prediction system (EPS) at ECMWF shows that the realized predictability is mainly extended when the modelling of dynamical instabilities and the assimilation of data are improved. *Simmons (2006)* demonstrated that re-forecasts from the ECMWF re-analysis (ERA) with a model system for data-assimilation and predictions have a much smaller trend in prediction quality over the ERA period than the trend experienced in real time when the methods developed.

A practical consequence of limited predictability is that the information content in predictions (the prediction sharpness) must be reduced in order to be reliable throughout the forecast range. If any event is predicted to occur with probability either 1 or 0, the information content is the maximum possible and the sharpness is 1. When forecast probabilities equal the probabilities inferred from climate statistics, the forecast sharpness is 0, in accordance with the definition of weather forecasts. If forecast sharpness is negative, the information is more diffuse than in the climate statistics.

For well calibrated systems for weather prediction, the combined statistics for all forecasts at any lead time (including the initial analysis) equals the climate statistics for the site and date in question. Any order of moment for the prediction statistics (i.e., the pdf) will then be without systematic errors, and the predicted probabilities will be reliable at any forecast lead time. A forecast of the probability of an event is reliable if the event is observed to occur with the same frequency as the predicted probability among the cases when the particular probability is predicted. This implies that well calibrated predictions are fully reliable at any lead-time, but the information content decreases from (almost) 1 at initial time to 0 at the time of loss of predictability. The range of predictability is characterized by limitations in state-dependent predictability and in numerical prediction capabilities. The latter depend on initial condition uncertainty as well as uncertainties and errors in the prediction method – i.e., the model.

From theory for free turbulence, the three-dimensional small-scale turbulence implies much faster upscale contamination of predictability than the two dimensional quasi-geostrophic turbulence (e.g*., Lilly, 1984*). In practice, however, there are systematic structures in atmospheric flows associated with characteristic weather phenomena which tend to counteract this free turbulence view, and there are also interactions between the relatively predictable large-scale flows and geographically fixed surface forcing (orography, coastlines etc.) which produce small-scale structures with similar predictability as the large synoptic scales (*Anthes et al. 1985; Boer, 1994 and 2003; Simmons, 2006; Jung and Leutbecher, 2008)*.

A natural approach to weather forecasting would then be to give a gradually increasing level of detail as the forecast target approaches in time, starting with statistical quantities containing low levels of information sharpness in the extended range, and ending with sharp information on well defined localities in the short range. In addition, an ability to accurately describe/predict fine-scale ground surface properties may extend the predictability of small-scale features which are associated with strong surface forcing.

For extreme weather events - e.g., polar lows - the ambitions for the extended and medium range would be to forecast sea-ice structures, SST and the large-scale atmospheric patterns in which such events may be confined, while probabilities for strong winds and precipitation amounts on given localities will be the aim for the short and very short range predictions.

Polar region weather differs from mid-latitudinal weather in many respects, and conventional observations are also much sparser than at mid-latitudes. The planetary wave regime connected with the baroclinic westerly jet streams at mid-latitudes is to a large extent absent. Inside the Arctic basin, almost barotropic situations prevail, but with a low-level Arctic front close to the ice-edge and Arctic snow cover. This Arctic front is particularly strong in winter, and there may be intense wind systems associated with it (*Grønås and Skeie, 1999*).

Figure 26 shows that regular verification statistics for the ECMWF probabilistic forecasts are generally worse at high latitudes than for the entire extratropical hemispheres. For the shown forecast parameter (500 hPa geopotential height) and the chosen winter periods, the difference implies a reduced forecast quality of up to more than a day lead time in high southern latitudes. The difference between the Arctic and the entire northern hemisphere is considerably smaller, but for other parameters and periods — e.g., for 850 hPa temperature from November 2010 through February 2011 — the difference is similar to results shown for the Antarctic in Figure 26. Similar results are also be found for root mean square error of the 500 hPa geopotential height for the high-resolution deterministic forecasts from ECMWF (not shown). (See Figure 29 and Figure 30 for probabilistic scores for short-range predictions in the Arctic.)

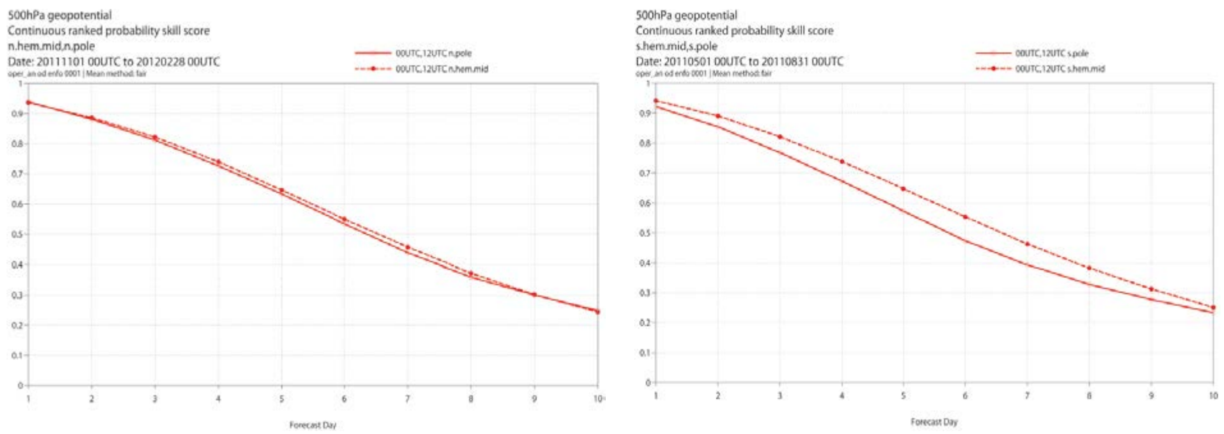


Figure 26 - The continuous rank probability skill score (CRPSS) for the ECMWF probabilistic forecasts of 500 hPa geopotential height over extended 4-months winter periods. Left: November 2011 through February 2012 for the NH extratropics (dashed), and the area north of 65°N (continuous). Right: May through August 2011 for the SH extratropics (dashed), and south of 65°S (continuous).
(Source: *L. Magnusson*, ECMWF)

When larger-scale flow-patterns normally associated with the mid-latitudes cause extended meridional flows, very intense small-scale (50 - 500 km diameter) and hurricane-like cyclones may form in winter and spring when cold air flows across the ice-edge over the open ocean. Such **polar lows** tend to form beneath cold upper-level troughs or large scale lows when cold arctic air flows towards lower latitudes over a warm body of water. *Kristjánsson et al. (2011)* note the "… complex interplay among low-level baroclinicity, upper level forcing, sensible and latent heat fluxes, and latent heat release contribute to polar low genesis and intensification".

Polar lows last on average only a day or two. They can develop rapidly, reaching maximum strength within 12 to 24 hours of the time of formation. They often dissipate just as quickly, especially upon making landfall. In some instances several may exist in a region at the same time or develop in rapid succession. It is a serious issue for scientifically based weather forecasting, occasionally with fatal consequences for human life and property, that whilst some polar lows are satisfactory predicted with lead times longer than their development time, others are completely missed even in the very short range.

Kolstad (2011) gave statistics for the occurrence of polar lows in the Arctic and the Antarctic winter. He found that preferred regions in the Northern Hemisphere are, respectively, the Labrador Sea region and the Nordic Seas. In the Southern Hemisphere, favourable conditions occur substantially less often than in the North. Northern Hemispheric polar lows mostly occur between November and April with a maximum frequency in January and March. In winter, larger scale cyclones are formed in mid latitudes and propagate into the Arctic. A negative mean sea-level pressure anomaly over most parts of the pole (centred on Greenland) favours the propagation of cyclones propagating from the South-West into the Nordic sea and the Arctic, and polar lows then form in the cold air outbreaks in the wake of the troughs (*Noer et al. 2011*).

Arctic summer is to a large extent associated with low-levels cloudiness and fog. The sea-ice can be open over large areas and there are occurrences of large intermittent lakes of melt water on top of the ice.

Climatological studies over the southern hemisphere indicate that there is a positive relationship between the regional extent of Antarctic sea ice, the longitudes of preferred occurrence of cold air outbreaks and the incidence of polar lows (*Carleton and Carpenter, 1990).* In the more interior parts of the Antarctic continent the thick ice sheet and the topography provides very different conditions than in the Arctic. The small amounts of precipitation and the cold dry air makes it reminiscent of desert conditions. Strong katabatic winds may occasionally develop.

Potential predictability of weather is associated with the difference (or ratio) between the total actual climatic variability and the variability caused by the atmosphere alone. Even though some variability may stem from changes in the input of energy from the universe (e.g., changes in solar radiation), processes in the oceans and the land-surface provide sources for potential predictability. In the Arctic and Sub-Arctic, sea-ice and snow cover are important. The variability in the middle and upper atmosphere can also be regarded as a source of potential predictability.

In order to realize the potential predictability in practical predictions, the sources of non-atmospheric variability must be predicted. The fact that considerable parts of the non-atmospheric variability result from exchange processes with the atmosphere, however, makes this task complex and challenging. In the Arctic, and to some extent in the Antarctic, prediction of all aspects of sea-ice is important.

Potential predictability is associated with ground surface and oceanic processes and concerns extended-range predictions on monthly, seasonal, and (possibly) longer time scales. The relevant processes in oceans and the ground surface are regarded as providing extended "memory". For monthly forecasts and longer, properties of the upper oceans and the land surface may even be the main aim of the forecast. Furthermore, potentials for extended-range predictions at polar latitudes rely on a global scope.

Whilst extended-range predictions would be entirely unimaginable without the existence and ability to predict non-atmospheric features, short-range and early medium-range predictions may be influenced and improved by them. Thus, in the Arctic and along the Antarctic boundaries, short-range predictions may benefit by high-quality prediction of exchange processes with the upper ocean layers, the sea-ice, and the land surface.

The surface albedo may change abruptly when snow cover and sea-ice varies in response to atmospheric processes. Furthermore, the fluxes of latent and sensible heat in the marine boundary layer may change quickly when and where there is upwelling of sub-surface warm water. For example, strong wind-driven mixing in the upper levels of the ocean may produce positive feedbacks for polar low developments by increasing the SST (*Sætra et al. 2008*), although this effect is not yet quantified. *Linders and Sætra (2010)* demonstrated that CAPE is too quickly consumed to represent a reservoir of energy for polar lows, indicating that this quantity must be continuously replenished in polar lows, probably from the open ocean surfaces over which they develop quickly and are sustained until land-fall.

7.2 Short Range

Scientific development of understanding and methods to underpin operational short-range forecasting has (in 2012) reached a considerably less mature stage than for the medium-range. While it is expected from experience that forecasts beyond 3 days are uncertain and can fail seriously, forecast errors for the first 1-2 days at middle latitudes are much smaller. Short-range predictability of large-scale fields of pressure, temperature, and quasi-geostrophic flow in the lower and middle troposphere is indeed generally very high. Traditional verification statistics confirm this. For example, operational verification of the deterministic forecasts of 500 hPa geopotential in the extratropics now yield more than 97% anomaly correlation for 3-day forecasts, which is close to perfection. Alternatively, as shown in Figures 16.17 and 16.18 in Simmons (2006), the anomaly correlation for this parameter has been 99% or higher for forecast lead-times of 1 day or longer since the early 1990s, and for 1.5 days or longer by in 2003/2004.

Inspired by such verification results, it is tempting to exaggerate other aspects of the short-range predictability. Hence, views have been expressed that questions the need for probabilistic elements in such forecasts. However, more directly weather-relevant variables, which involve smaller spatial details, will not show anything similar to the high scores for the 500 hPa geopotential. For example, Figure 27 shows probabilistic scores over European observation sites for 4-day predicted events for 24 h precipitation amounts and 10 m wind speed, clearly demonstrating this. The quality decreases for the extreme events, and there is little skill for wind speed event predictions.

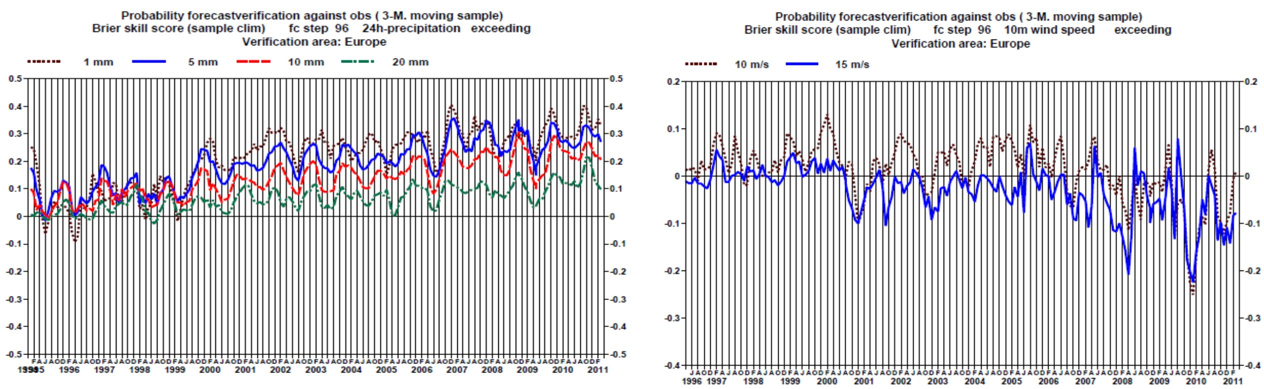


Figure 27 - Brier Skill Score for 4 event thresholds of 24-h precipitation (left) and 2 event thresholds of 10m wind speed (right), forecasted by the operational ECMWF EPS at 4 days lead time since 1996. Verification against European observations

Figure 28 (from *Jung and Leutbecher, 2007*) shows verification statistics for deterministic 2-day and 5-day forecasts of 500 hPa geopotential height for areas poleward of 70º in both hemispheres. Re-forecasts from the ERA-40 analyses are also shown along as well as temporal standard deviation of the analyses, and it is striking to see that the southern hemisphere variability is smaller and that 5-day forecasts did not have any predictive skill before ca. 1980 when satellite data started to be used. Measured by the fraction of the analysis variability, the northern polar region used to be more predictable than the southern but the difference is now small. The figure also demonstrate that prediction quality has increased in polar regions mainly due to improvements in the methods for data-assimilation and numerical prediction rather than changes in the observations (as shown by *Simmons (2006)* for the entire extratropics).

Jung and Leutbecher (2007) also investigated the impact of model resolution for one-day forecast tendencies from day 2 to day 3 of 500 hPa geopotential. This indicated a smaller impact of resolution in the Arctic than over the storm-track regions at northern hemisphere mid-latitudes. However, the resolution difference was only a factor of 2 and the 500 hPa geopotential is spatially smooth. Nevertheless, major improvements in the ECMWF ensemble prediction system for the arctic area north of 65ºN, as measured by the Rank Probability Skill Score (RPSS) for 5 percentile thresholds for the forecast probability, are predominantly ascribed to increased model resolution. By calculating adjoint sensitivities, they also found that 2-day model errors in the Arctic are influenced by processes in the North-Atlantic storm track, but that this contribution is highly situation dependent. This indicates that even short-range Arctic NWP should be based on EPS.

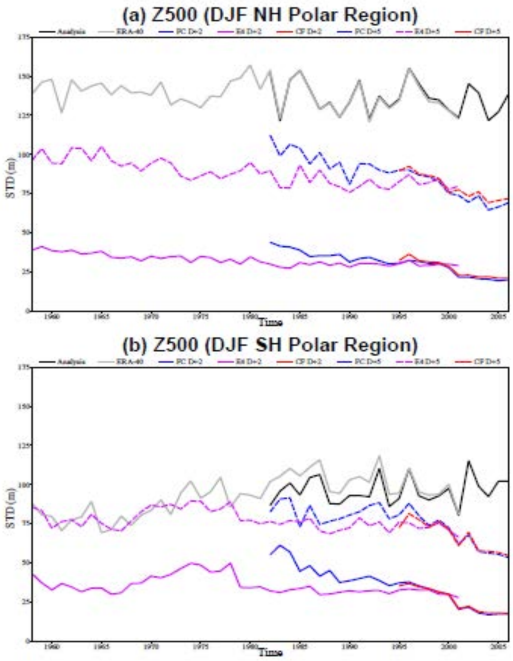


Figure 28 - Time series of the temporal mean spatial standard deviation of daily Z500 forecast error at D+2 (solid lines) and D+5 (dashed lines) for the (a) Northern and (b) Southern Hemisphere polar region (poleward of 70N and 70S). Three different forecast sets are used: operational deterministic forecasts (blue), EPS control forecasts (red) and ERA-40 re-forecasts (purple). Also shown are time series of the mean spatial standard deviation of Z500 fields from operational analyses (black, solid) and ERA-40 reanalysis (grey, solid).
(*Jung and Leutbecher, 2007*)

Over the first 3-4 decades of modelling for NWP, the model output mainly were basic dynamic variables which contain little direct information on weather characteristics in regions or localities. Post-processing and interpretations were needed. Direct weather-relevant information gradually became available as the computer power allowed to resolve weather-specific features and enabled more realistic parameterizations of physical processes.

With an increasing use of direct output from model forecasts it is realized that an almost perfect forecast of the hemispheric 500 hPa geopotential does not translate into an almost perfect forecast for users. A range of variables that directly describe weather elements are considerably more sensitive than pressure fields, and verification is prone to vary between regions and local sites. Figure 27 clearly demonstrates this.

Reduced probabilistic scores in the Arctic are furthermore documented with a short-range, limited area EPS run in a domain including parts of the Euro-Atlantic sector of the Arctic by *Aspelien et al. (2011);* see Figure 29 and Figure 30. Even though the scores indicate better probabilistic forecasts than the ECMWF up to 36 h lead time, the quality is worse north of 65°N than in the entire domain. The system also demonstrates the benefit of a multi-model approach, which is further confirmed by *Iversen et al. (2011).*

Aspelien et al. (2011) as well as *Kristiansen et al. (2011)* investigated how ensembles with high resolution model forecasts can be used to forecast extreme weather associated with polar lows which were extensively observed during IPY THORPEX (*Kristjánsson et al. 2011*). Randiamampianina et al. (2011) also investigated if modern satellite data (IASI) utilized in 3D-Var can improve polar low forecasting. The largest positive impacts of the remotely sensed data are found when there also are more in situ observations are available. This emphasizes a need for more regular conventional observations in the Arctic.

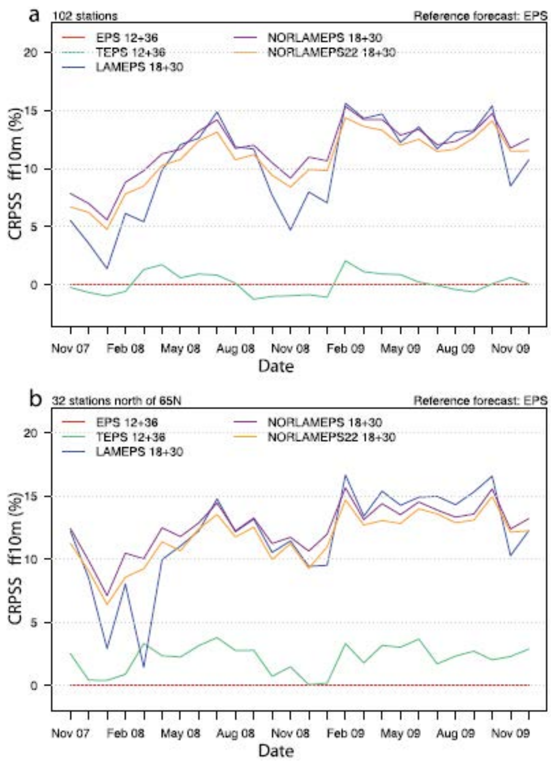


Figure 29 - Continuous rank probability skill scores (CRPSS) with operational ECMWF EPS as reference for wind speed at 10m height and 30h lead time starting from 18 UTC. ECMWF EPS (red), ECMWF TEPS(green), LAMEPS (blue), NORLAMEPS (purple), and NORLAMEPS22 (orange). Add 6 h to the lead-times for EPS and TEPS. (*Aspelien et al. 2011*)

(a) At 104 European verification sites
(b) At 32 European sites north of 65°N

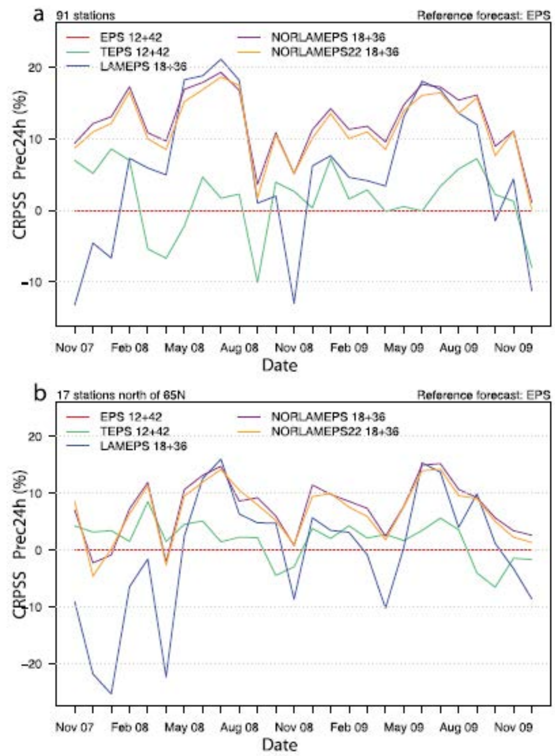


Figure 30 - As for Figure 29 but here for 24 hourly accumulated precipitation over 12–36 h lead time starting from 18 UTC

(a) At 91 European verification sites
(b) At 17 sites north of 65°N

7.3 Medium Range

Between forecast lead-time 2 and 10 days the relative contribution between the initial condition and model error contribution changes dramatically; however, the accuracy of the initial conditions is always important throughout the medium range. Into the medium range the interaction of the troposphere with the stratosphere and the interaction between atmosphere, land, sea-ice and ocean become more important. A reliable medium range forecasting system must therefore deal with providing accurate initial conditions for all of them and explicitly account for all associated physical processes that are driving the coupling.

In most medium-range prediction systems, sea-surface conditions such as SST and sea-ice coverage are prescribed from observations at analysis time and then persisted into the forecast, either as constants or as constant anomalies. This saves performing a (coupled) ocean/sea-ice analysis and running a coupled forecast over the medium range. Hindcast experiments (Figure 31 and Figure 32,) indicate that the medium-range predictability of near-surface temperatures and wind increases when actual SST/sea-ice are taken into account. If this necessarily produces improvements in boundary layer and cloud physics as well as upper air dynamics is uncertain.

The troposphere-stratosphere interaction is aligned with the formation and maintenance of the polar stratospheric vortex and its break-down causing so-called sudden stratospheric warmings (SSW). These are initiated by upward travelling large-scale planetary Rossby waves where the wave energy dissipates in the stratosphere and thus decelerates the mean vortex flow. The SSW occur primarily over the Arctic and can be followed by a surface pressure response that is most pronounced beyond the medium range (*Baldwin and Dunkerton, 1999; Jung and Leutbecher, 2007*). Also, there is an interaction between SSW and the Quasi Biennial Oscillation (QBO) when it is in its easterly phase (*Labitzke and van Loon, 1999*); however also this applies more to the extended range.

7.4 Extended Range

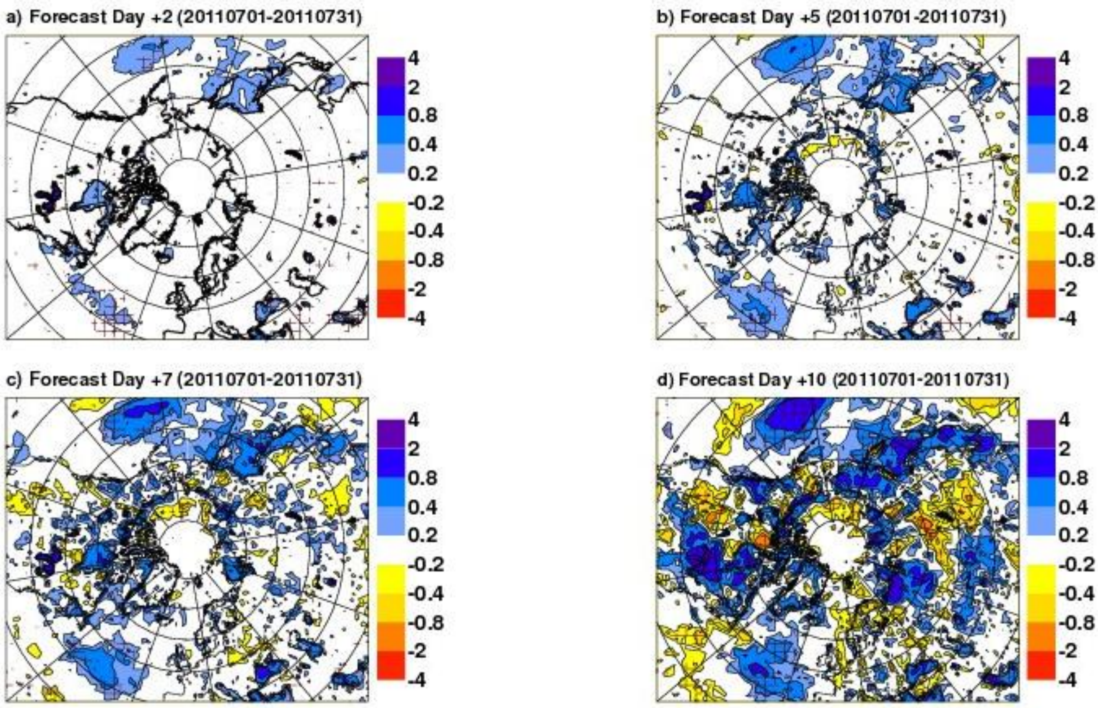
Extended range forecasting, here defined as forecasts on monthly to multi-annual timescales, is important for assessing marine access to the remote polar regions. This access is highly variable and these variations can incur considerable logistical challenges, with substantial associated costs, for things like re-supply efforts and scientific accessibility. As such, there is a critical need for reliable predictions, with quantified uncertainty, for Arctic and Antarctic conditions on monthly to inter-annual timescales. This is only likely to increase as secular changes in the polar regions enhance marine accessibility but could also make it more variable and subject to extreme events.

Our understanding of the inherent predictability in polar regions on extended range timescales is incomplete and to-date limited research has been performed on this topic. At the monthly to inter-annual timescales, coupling across the atmosphere-ocean-terrestrial system becomes increasingly important as the more slowly evolving aspects of the system, related for example to the large thermal inertia of the ocean, can provide a useful source of memory, i.e., potential predictability.

Because of the unique environmental conditions at and around the Poles, the results from predictability studies focused on other regions do not necessarily translate to our understanding of polar predictability. For example, the sea ice cover could provide an important source of memory to the system that is not present at lower latitudes. This may enable some predictive skill at longer timescales. Previous work does suggest a longevity of sea ice anomalies and the possibility of “reoccurrence” of sea ice variations seasonally or interannually in both the Arctic (*Blanchard-Wrigglesworth et al. 2011*) and the Antarctic (e.g., *Gloersen and White, 2001*). These could in turn influence variations in the atmosphere, providing a possible source of predictability. Indeed, numerous studies including *Deser et al. (2010) and Balmaseda et al. (2010*) have found some robust and significant atmospheric response to sea ice variations.

Figure 31 and Figure 32 show results from hindcast experiments in which the impact of observed and persisted sea-ice and SST on 2-metre temperature analyses and forecasts is evaluated. 2011 has been affected by larger than usual sea-ice melting in northern polar summer so that accounting for the evolution of sea-ice along 10-day forecasts is likely to be important. The results suggest that (1) representing the actual SST evolution mainly affects storm tracks while (2) sea-ice dynamics effects are more localized near the ice edge and change sign between months of melting (Figure 31) and freezing (Figure 32d). Similar results are produced when ensemble mean forecasts are compared.

Including dynamic sea-ice and SST in medium range forecasts improves low-level temperatures until day-10 and some improvement of wind forecasts is noted as well.



Fiigure 31 - Mean 2-metre temperature difference between hindcast experiments using observed and persisted sea-ice/SST for July 2011. Panels denote analysis (a), day-5 (b), 7 (c) and 10 (d) forecasts

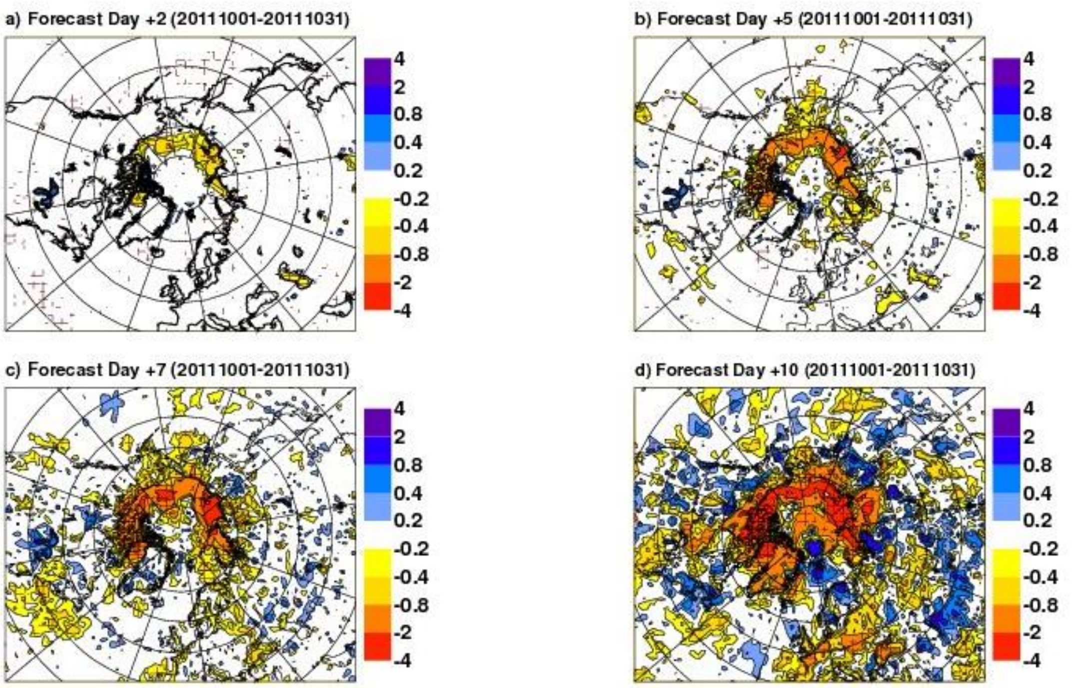


Figure 32 - As in Figure 31, but for October 2011

7.5 Diagnostics

Our understanding of the dynamical and physical processes that are relevant for forecasting depends on the time scale and region being considered. In polar regions, for example, short-range weather forecasts are mainly influenced by local boundary layer processes and micro-physics; on longer time scales, however, processes in remote regions (for example, mid-latitudes and tropics) become increasingly important. In general, there are a number of well-known forecast relevant processes. However, it can be argued that we do not have a complete list of such processes and generally there is a lack of quantitative understanding of their relative importance. In fact, this lack of knowledge is appreciated by the wider community as highlighted by the first results from the WCRP Community-wide Consultation on Model Evaluation and Improvement.

Two different approaches are used as part of model development. The first approach is well-established and can be described as "bottom-up" in which new or improved physical parametrization schemes (or numerical formulations) are based on theory, observations or cloud resolving model studies. The second approach can be described as "top-down"; in this *diagnostic* approach model problems are identified, for example through the use of metrics. In practice, the next step is to modify the model somehow and to "hope" that the problem will be alleviated. Finding methodologies that can identify model errors at the process level would greatly improve the benefits of the "top-down" approach. Understanding the origin of model problems through diagnostic studies would also help to prioritize model development.

A wide range of diagnostic techniques have been developed in recent years. A technique can be considered as being of diagnostic value if it helps to understand the origin of model problems at the process level. This is in contrast to other equally important but more descriptive techniques such as metrics or verification. One important aspect is the fact that diagnostic techniques that can be used to understand the origin of model problems at the process level are potentially equally powerful in enhancing our understanding of the functioning of the atmosphere/climate system (for example in extra-tropical cyclones and mountain torques) and vice versa.

For high-resolution forecasting in the short and very short ranges, it has proven difficult to match the need for high-resolution description of specific atmospheric features, such as deep convective systems, sharp fronts, and squall lines, and the actual ability to forecast such features based on initial state analyses. The large growth rate of small-scale features, leads to strong requirements for very accurate as well as frequent analysis updates, so-called Rapid Update Cycling (RUC). Until adequate accuracy and frequency are obtained, spatial model resolution may resolve a range of unpredictable features. This will lead to double penalty when evaluating the forecast with standard verification metrics, giving objective benefit to low-resolution models. In this situation, part of the diagnosis should be the estimation of predictable scales, for example by estimating the spatial scale for which a parameter like the Fractional Skill Score (FSS) reaches a minimum predictable level (*Roberts and Lean, 2008*).

7.6 Key Challenges

7.6.1 Short Range

The key scientific challenges for enhancing short-range predictability are:

- Why are still some polar lows still completely missed by short-range EPS and deterministic NWP? Are processes missing or erroneously parameterized in the models? Are initial states missing information? Are the surface boundary conditions wrong? Do we need cloud-resolving NWP models to obtain describe the growth mechanisms adequately? This is arguably one of the most prominent research issues for the short and very short range predictability in polar areas.

- Compared to the mid-latitudes, there are very few NWP studies in polar latitudes, in particular in the Antarctica (although examples there include *Bromwich et al. 2005; Nigro et al. 2011*). Given the larger immediate impacts of Arctic weather on human settlements and activities which may enhance in the near future, an increased NWP activity for short range, high resolution probabilistic studies is needed. This is in particular the case in regions prone to polar lows and other meso-scale extreme weather systems (topographic effects, low-level jets).
- The benefit of coupling atmospheric short-range EPS with the oceans and sea-ice needs to be investigated. There are potential positive feedback effects in polar lows driven by continuous CAPE replenishment as wind-driven mixing of the upper ocean may increase the SST near the centre of the polar low.
- Data-assimilation of advanced satellite date may be under-exploited due to the very sparse network of conventional in situ observations. Regular observations are needed to be taken more frequently and in more places than now.
- The ability to use radar data should be developed also in polar areas, at least in areas where polar lows develop. Even if regular data assimilation may have problems to extract relevant data from single radars for operational NWP, they can mean the difference between life and death if made available to weather forecasters.
- The frequency of analyses (and thus forecast updates) should be in balance with the growth rate of polar lows and other extreme weather situations. How frequent should be a subject of research, in connection with predictability studies and development of relevant data –assimilation techniques for the short range.

7.6.2 Medium Range

The key scientific challenges for enhancing medium-range predictability are:

- Enhanced model resolution (horizontal and vertical) has clearly helped to improve medium-range predictability (see Figure 33 and Figure 34). At present, even global ensemble prediction systems are run at resolutions that resolve the most important synoptic and large-scale features.
    - The importance of further increasing resolution needs investigation. A sub-aspect of this is the required resolution in the analysis that is currently by a factor of 3-5 coarser than that of the forecast model. The resolution aspect seems most relevant to the representation of polar lows that have small dimensions and short lifetimes but rather high intensities as well as when the large scale flow interacts with orography (e.g., gravity waves over the Antarctic peninsula, *Rabier et al. (2012);* flow across Greenland, *Jung and Rhines (2007)).*
    - Part of a seamless prediction approach is the reduction of resolution through the short-to-extended forecast range. The change in resolution accounts for the fact that smaller scales become less predictable at longer time scales and it also reduces the computational effort. It also affects the representation of model physics (scale dependent parameterization) and thus systematic errors and model climate. A challenge is to estimate the optimal switching points and how to avoid introducing shocks that cause imbalance and intermittent spin-ups.
    - Equally important is vertical model resolution and its relation to physical processes. This pertains both to gravity waves in the stratosphere and to many parts of the parameterized physics in the lower troposphere (clouds, boundary layer, etc.).
    - The location of the model top in relation to resolving troposphere-stratosphere interactions requires investigation. At ECMWF, the deterministic and ensemble systems are run with 0.01 and 5 hPa, respectively. For example, over mid-latitudes raising the model top of the EPS did not show medium-range benefit so far.

- The role of the stratosphere for medium-range weather prediction needs to be better understood given the observed link between SSW and mean surface pressure variations beyond the medium range.
- The role of interactive sea-ice and the ocean from day-1 in both deterministic and ensemble forecasting systems needs evaluation. This question is strongly linked to the initial conditions that need to be produced in coupled or balanced mode (spin-up issues). It is also connected to the link between surface and boundary layer/clouds/radiation, particularly if snow on sea-ice is modelled (freezing/melting); see Section 3.1.
- The role of the lower latitudes in determining medium-range forecast skill in the polar regions needs to be quantified (see Section 8).
- The performance of medium-range ensemble prediction systems need to be evaluated for the polar regions given that they have been designed with the mid-latitudes and tropics in mind (see Section 6).
- Medium-range predictability in polar areas is strongly linked to in how far data assimilation systems can be optimized for polar conditions (EDA for state-dependent BG errors, model error formulation in ensemble systems, role of coupled DA, observing system characteristics (coverage, anchoring observations, quality control, bias correction); see Section 5)

Figure 33 and Figure 34 show analysis tendencies and 48-72 hour forecast error growth statistics over both poles for the period 2006-2011, similar to *Jung and Leutbecher (2007),* from the ECMWF operational high-resolution model, the EPS low-resolution control forecast and the ERA-Interim forecasts. The following conclusions, relevant to medium-range predictability over the poles can be drawn from this:

- As *Jung and Leutbecher (2007)* indicated, the analysis tendencies identify areas were day-today variations of geopotential height point at regions with strong baroclinic activity in which forecast errors are likely to grow faster than in other areas. These areas are located over the North-West and Southern Atlantic and Pacific oceans. Opposite to the 2006 system, forecast errors are smaller than analysis tendencies even until day-8 in 2011, indicating that there is predictability into the medium range now.
- The differences between high-resolution and low-resolution versions of the operational ECMWF model are small and decrease over time due to improved initial conditions and model developments. This suggests that the current resolution of the EPS (T639 - i.e., 30 km) captures the synoptic variability rather accurately.
- The analysis differences (not shown) between ERA-Interim (80 km) and the operational system (40/25/16 km) are small for this period (larger before 2006). However, the forecast differences between ERA-Interim and the operational model increase significantly with time, mostly due to model improvements. Note ERA-Interim used a 2006 version of data assimilation system and model.

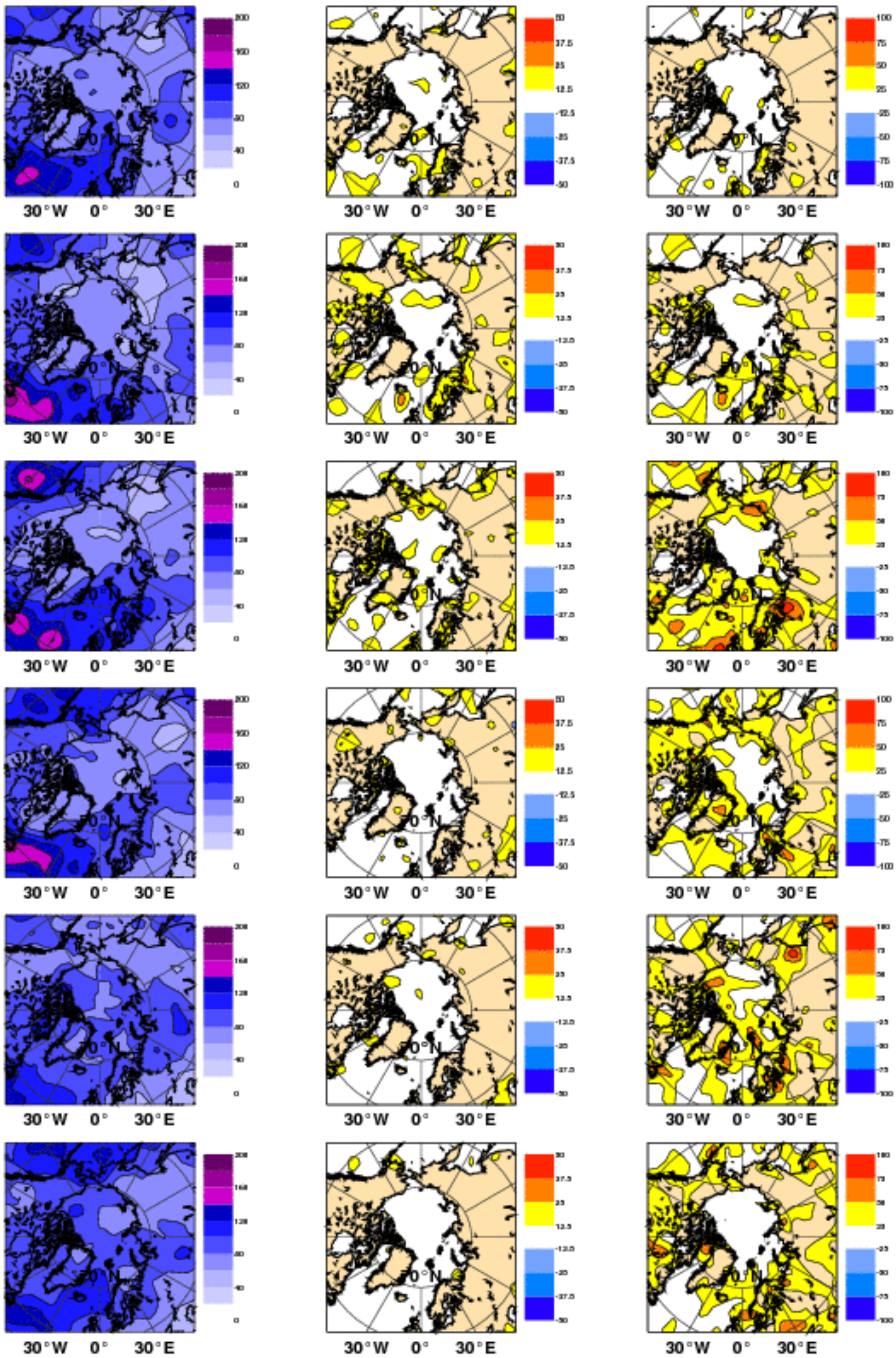


Figure 33 - Time series from DJF 2006 to DJF 2011 (top to bottom) of 500 hPa geopotential height daily tendencies (left column) and 48-72 hour forecast error growth of 500 hPa geopotential height, difference between high-resolution operational and low-resolution EPS control forecasts (middle column) and between high-resolution operational and ERA-Interim forecasts (right column) over the North Pole. Note different scales of middle and right columns

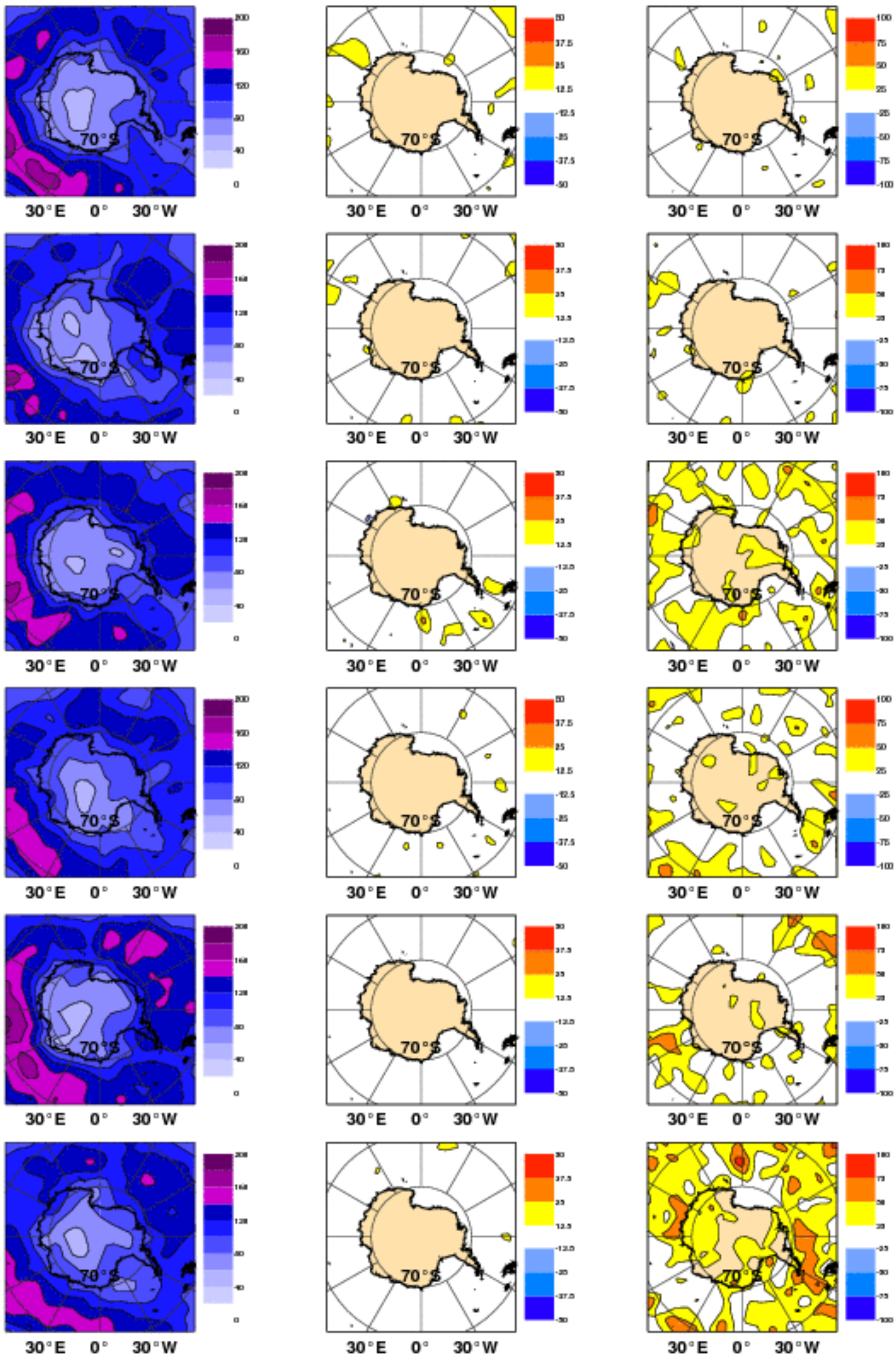


Figure 34 - as in Figure 33 but for JJA 2006-2011 over the South Pole

7.6.3 Extended Range and Sea-Ice

To develop better predictive tools requires a better understanding of the processes and feedbacks that provide predictive capability on the seasonal to multi-annual timescales. Additional foundational academic research is needed to address this through for example, potential predictability experiments with coupled models. However, due to biases in coupled model systems, coordinated experiments with numerous models will be needed to provide information on the robustness of model results. These experiments can provide insight on the predictability that is inherent in the polar climate system.

The ability to realize the inherent predictability for real world applications is limited by incomplete observations and flawed numerical models. Observational data is particularly limited in polar regions, leading to a large reliance on satellite observations. While satellite observations provide a useful characterization of some atmosphere and sea ice conditions, they provide little information on the underlying ocean. Issues with observational data sparseness, incompleteness, and bias are a critical challenge in terms of adequately initializing coupled model forecasts. Future research efforts should explore what aspects of model initialization errors could degrade extended range forecasts. This should include work on robust data assimilation techniques as a potential method to obtain useful initial conditions.

Model improvements are also needed to further our capacity to provide useful extended range predictions. Studies are needed to characterize the role of model resolution and parameterization uncertainty on aspects of extended range predication in polar regions. These would benefit from coordinated model-intercomparison activities and also from sensitivity simulations within individual models where the role of horizontal and vertical resolution and model parameterizations on predictability characteristics can be established. We note that these experiments should target model parameterizations throughout the coupled system, including atmosphere, sea ice, ocean, and terrestrial systems. Uncertainty quantification tools can provide a useful means to determine which parameterizations result in critical uncertainties. New observational comparison capabilities, such as the Cloud Feedback Model Intercomparison Project (CFMIP) Observation Simulator Package (COSP), allow for a more robust comparison of model results to satellite observations. This may allow more targeted model development activities of relevance to extended range polar prediction. As computational resources increase, higher model resolutions and increased ensemble size should also allow for improved prediction.

To tackle a problem of this complexity will require coordinated activities and multi-disciplinary scientists that are invested in the science. It will also require considerable computational resources to perform and analyze large-ensemble integrations.

7.6.4 Diagnostics

The key scientific challenges for diagnostics are:

- Development and application of diagnostic techniques that help identifying model error at the processes level.
- Developing methods and score parameters that reliably identify predictable scales, in particular for extreme weather events in polar regions, in the short range

8. GLOBAL LINKAGES

8.1 Background

Improving our understanding of the linkages of the polar regions with other parts of the globe will be one of the key objectives of the polar prediction project. Research in this area will reveal how predictions in the mid-latitudes, subtropics and tropics will benefit from forecasting system improvements in the polar regions across a wide range of time scales. Furthermore, research will quantify how much of the actual and potential predictive skill in the polar region originates in the lower latitudes. Global linkages will need to be studied for the atmosphere and the ocean-sea ice system.

For the polar atmosphere the relative influence of remote regions depends on the time scale being considered. For a short-range forecast a few hours in length, for example, it is reasonable to assume that it is primarily local, polar processes that govern the evolution of the forecast. It should be kept in mind, however, that the analysis from which the short-range forecast has been started might have been influenced indirectly by remote observations through cycling in the data assimilation processes. For forecasts beyond a few hours possible remote influences (both horizontally and in the vertical) have to be considered given the presence of relative fast wave processes in the atmosphere.

Adjoint sensitivity studies show that 2-day forecasts for the Arctic atmosphere are already significantly influenced by perturbations in the mid-latitudes (*Jung and Leutbacher, 2007*), with the largest influence coming from the North Pacific and especially the North Atlantic storm track regions (Figure 35). Furthermore, the mid-latitude influence on the Arctic is clearly flow-dependent, with a strong link being favoured by the presence of large amplitude planetary waves (upstream of ridges) and hence the orientation of the polar jet stream. This flow-dependence highlights the importance of ensemble forecasting in polar regions.

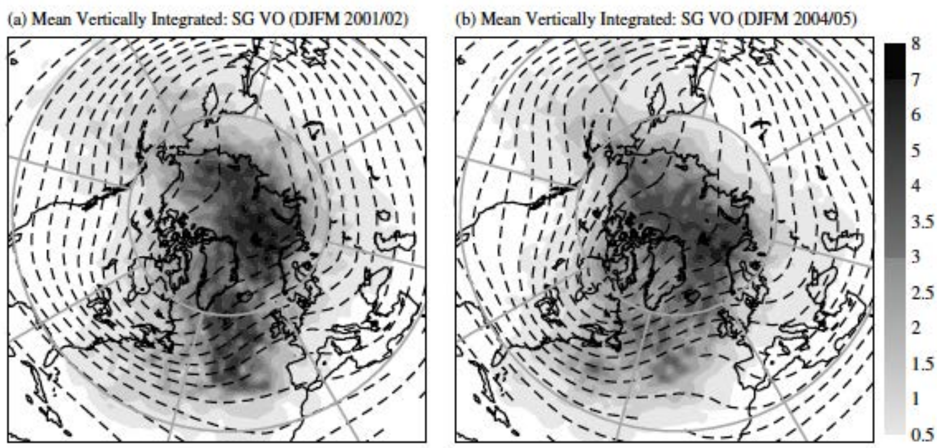


Figure 35 - Mean of vertically-integrated absolute value of daily sensitivity gradients of D+2 forecast error north of 70°N to tropospheric initial perturbation of vorticity (shading) for two winters (December-March): (a) 2001/02 and (b) 2004/05. Large (small) values indicate a large (small) influence on subsequent forecast error over the Arctic. Also shown are winter mean values of 300 hPa geopotential height (contour interval, 100 m) (from *Jung and Leutbecher, 2007*)

There is little quantitative knowledge at present as to how strongly the mid-latitude processes influence prediction skill in the polar regions in the medium-range and beyond. However, given the important role of mid-latitude transient eddies for the momentum, energy and hydrological cycle of the polar regions, a strong linkage can be expected.

The influence of the tropics on the Northern Hemisphere and Southern Hemisphere extratropics including the polar regions is relatively well understood, especially on longer sub-seasonal and seasonal time scales. It is well known, for example, that ENSO influences both polar regions through Rossby wave propagation (e.g., *Schneider et al. 2011*). For the Northern Hemisphere it has been argued that polar vortex variations and their downward influence on the Arctic troposphere are involved in this link (e.g., *Bell et al. 2009*). A downward influence of the stratospheric polar vortex is also likely to be operating over the Southern Hemisphere. Furthermore, there is mounting evidence that the Madden-Julian Oscillation can influence the Northern Hemisphere polar region through its influence on the Arctic Oscillation (AO, *L'Heureux and Higgins, 2008; Lin et al. 2009*), as well a related impact on the North Atlantic Oscillation (*Cassou, 2008*). By analyzing the output of intraseasonal hindcasts *Lin et al. (2010)* have shown that the MJO has a significant impact on the skill of intraseasonal AO forecasts. On the other hand, the AO variability results in changes in the tropical upper zonal wind and the initiation of the MJO (*Lin et al. 2009*). In *Lin and Brunet (2011)* it was demonstrated that the AO also has an important influence on the forecast skill of the MJO. Intraseasonal forecasts would benefit from such an interaction if such a process can be resolved in forecasting systems.

Relatively little is known about how exactly the polar atmospheres influence the lower latitudes. This is in stark contrast, for example, to the good dynamical understanding we have about tropical-extratropical and extratropical-tropical atmospheric interactions. Given the rapid changes observed in the polar regions, especially in the Arctic, a thorough understanding of atmospheric linkages between the polar regions and lower latitudes is of crucial importance. Furthermore, current weaknesses in our polar observing systems (e.g., sparseness of observations) and problems of models in representing important polar key processes suggest that predictive skill in the lower latitudes can benefit from improved forecasting in the polar regions; a deeper quantitative understanding of this point also requires a better understanding of atmospheric linkages between the polar regions and the lower latitudes from time scales of hours to a season.

There is some emerging knowledge about the possible remote impact of polar lows. Firstly polar lows can locally warm the SSTs by mixing warm water from below by 1-2 K (*Sætra et al. 2008*). This is a local forecasting issue and points to using coupled models for short/medium term NWP. Secondly polar lows affect both the local and global ocean circulation. *Condron et al. (2008)* showed they can spin up the Nordic Seas gyre, and in recent work *Condron and Renfrew (2013)* have extended this work showing they significantly enhance deep water formation in the Nordic Seas leading to significant changes in deep water overflowing Denmark Strait and this impacting on the Atlantic Subpolar Gyre. Given that the frequency and location of polar lows is predicted to change, drifting polewards as the sea-ice retreats (*Kolstad and Bracegirdle, 2008; Zahn and von Storch, 2010*) these impacts are important for both short/medium term forecasting and climate prediction.

Only a few studies so far have dealt with the impact of analysis and forecast improvement in the polar regions on forecast skill in the lower latitudes. The existing studies suggest that forecasting system improvements in the Arctic lead to improved short-range and medium-range forecast skill in part of the mid-latitudes such as Europe (*Klinker and Ferranti, 2000*) for certain types of atmospheric flow conditions. Cold air outbreaks associated with the presence of large-scale amplitude waves seem to be particularly favourable for an Arctic control of mid-latitude weather. The existence of polar lows as far south as Great Britain is a manifestation of this link.

The atmospheric response to changing sea ice conditions has been studied extensively in recent years. Some authors have reported mid-latitude responses (e.g., *Dethloff et al. 2006, Bhatt et al. 2008*) to Arctic sea ice anomalies, whereas others argue that any potential remote response to Arctic sea ice change are currently hard to confirm and remain uncertain (*Screen et al. 2012*). Perhaps the strongest atmospheric response has been found when sea ice extent in the Labrador Sea was reduced with a simultaneous increase of sea ice extent in the Greenland-Icelandic-Norwegian (GIN) seas (Figure 36, *Deser et al. 2007*). Whether this relatively large response is due to the proximity of the sea ice anomalies to one of the major baroclinic zones remains to be shown.

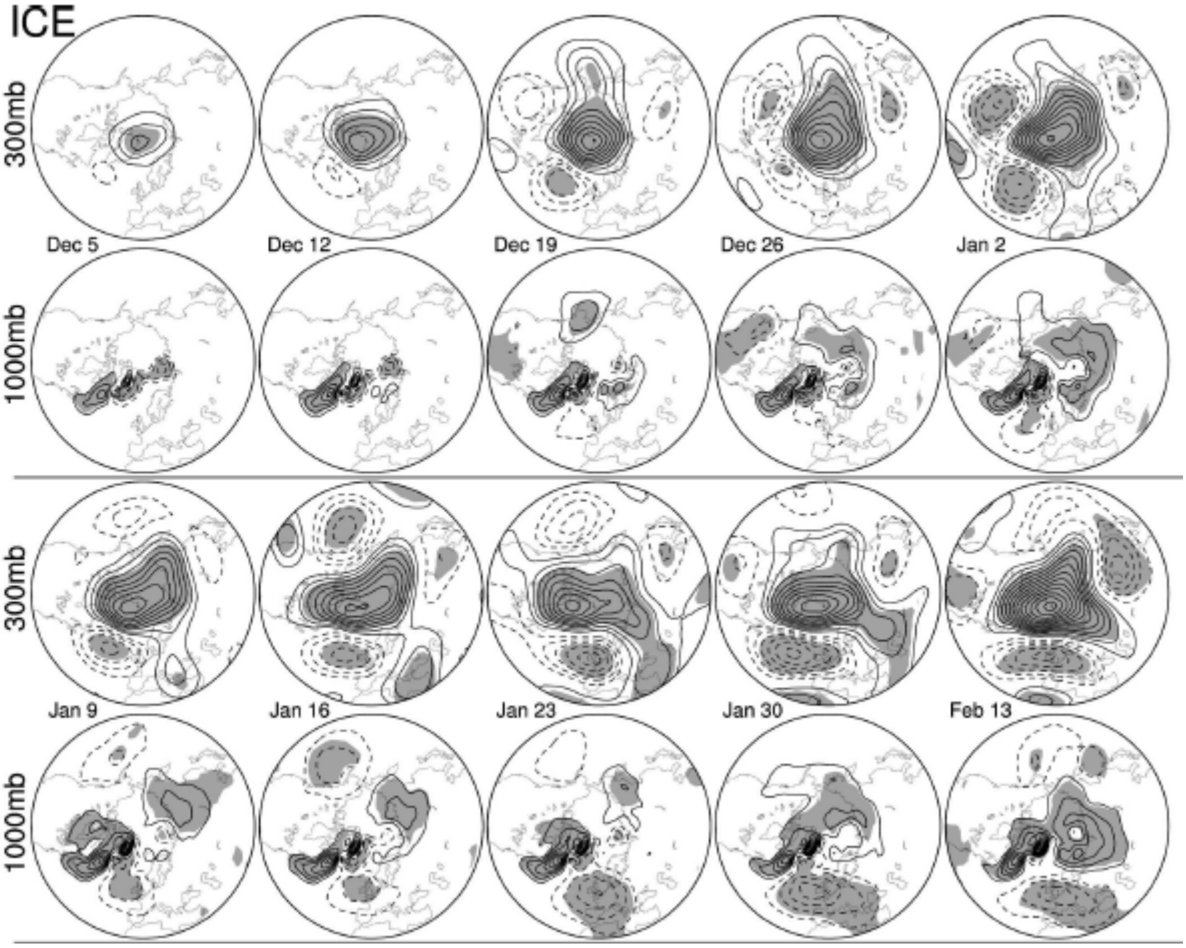


Figure 36 - Ensemble-mean 1000-hPa and 300-hPa geopotential height anomalies (contour interval is 10 m) for the first weeks (Dec 5=1 week, Dec 12=2 weeks and so forth) of an atmospheric model experiment in which the ice extent has been reduced in the Labrador Sea, and simultaneously increased in the Greenland-Iceland-Norwegian seas. (From *Deser et al. 2007*)

Global linkages between the polar regions and the lower latitudes can also be established through the ocean-sea ice system. It is well known that freshwater anomalies of polar origin can have significant influences on the ocean circulation through modification of deep water formation. Especially in the North Atlantic region, the inflow of relatively warm and saline Atlantic water has a profound influence on the thermodynamics and circulation of the Arctic ocean. Although most of the variability of the ocean-sea ice system can be found on interannual and longer time scales it will need to be considered for shorter-term sub-seasonal and seasonal predictions. This is because the paucity of observational data for sea ice and especially the ocean provides the first guess in ocean-sea ice data assimilation a relatively high weight, that is, the cycling forward of past atmospheric, oceanic and sea ice observations is crucial. Furthermore, sub-seasonal and seasonal predictions are likely to benefit from the presence of interannual and decadal SST and sea ice anomalies (seasonal ENSO forecasts are a prominent example). This is especially true if the atmospheric response changes throughout the course of the seasonal cycle.

8.2 Key Challenges

The key challenge during the project period will be as follows:

- To improve our understanding of linkages between the polar regions and the lower latitudes and their flow-dependence in the atmosphere-ocean-sea ice system from time scales of hours to one season.
- To obtain quantitative knowledge about how these linkages translate into remote origins of predictive skill and forecast failures, in order to guide future forecasting system development.

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