Advancing polar prediction capabilities on daily to seasonal time scales

Thomas Jung*

AWI, Bremerhaven, Germany and

University of Bremen, Bremen, Germany

Neil D. Gordon

Neil Gordon Consulting, Otaki, New Zealand

Peter Bauer

ECMWF, Reading, UK

David H. Bromwich

Ohio State University, Ohio, USA

Matthieu Chevallier

CNRM, Toulouse, France

Jonathan J. Day

Reading University, Reading, UK

Jackie Dawson

Department of Geography, University of Ottawa, Ottawa, Canada

Francisco Doblas-Reyes

IC3 and BSC, Barcelona, Spain

Christopher Fairall

NOAA, Boulder, USA

Helge F. Goessling

AWI, Bremerhaven, Germany

Marika Holland

NCAR, Boulder, USA

Jun Inoue

NIPR, Tachikawa, Japan

Trond Iversen

NMI, Oslo, Norway

Stefanie Klebe

AWI, Bremerhaven, Germany

Peter Lemke

AWI, Bremerhaven, Germany

Martin Losch

AWI, Bremerhaven, Germany

Alexander Makshtas

AARI, St. Petersburg, Russia

Brian Mills

Environment Canada, Waterloo, Canada

Pertti Nurmi

FMI, Helsinki, Finland

Donald Perovich

ERDC-CRREL, Hanover, USA

Philip Reid

Bureau of Meteorology, Hobart, Australia

Ian A. Renfrew

University of East Anglia, Norwich, UK

Gregory Smith

Environment Canada, Montreal, Canada

Gunilla Svensson

University of Stockholm, Stockholm, Sweden

Mikhail Tolstykh

INM RAS and Hydrometcentre of Russia, Moscow, Russia

Qinghua Yang

NMEFC, Beijing, China

[*] *Corresponding author address:* Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Bussestrasse 24, D-27570 Bremerhaven, Germany.

E-mail: Thomas.Jung@awi.de

ABSTRACT

The polar regions have been attracting more and more attention in recent years, fuelled by the perceptible impacts of anthropogenic climate change. Polar climate change provides new opportunities, such as shorter shipping routes between Europe and East Asia, but also new risks such as the potential for industrial accidents or emergencies in ice-covered seas. Here, it is argued that environmental prediction systems for the polar regions are less developed than elsewhere. There are many reasons for this situation, including the polar regions being (historically) lower priority, with less in situ observations, and with numerous local physical processes that are less well-represented by models. By contrasting the relative importance of different physical processes in polar and lower latitudes, the need for a dedicated polar prediction effort is illustrated. Research priorities are identified that will help to advance environmental polar prediction capabilities. Examples include an improvement of the polar observing system; the use of coupled atmosphere-sea ice-ocean models, even for short-term prediction; and insight into polar-lower latitude linkages and their role for forecasting. Given the enormity of some of the challenges ahead, in a harsh and remote environment such as the polar regions, it is argued that rapid progress will only be possible with a coordinated international effort. More specifically, it is proposed to hold a Year of Polar Prediction (YOPP) from mid-2017 to mid-2019 in which the international research and operational forecasting community will work together with stakeholders in a period of intensive observing, modelling, prediction, verification, user-engagement and educational activities. This is the end of the abstract.

(Capsule Summary) It is argued that existing polar prediction systems do not yet meet users' needs; and possible ways forward in advancing prediction capacity in polar regions and beyond are outlined.

The climate of the Arctic has been changing more rapidly in recent decades than any other region of this planet. The rapid rise in near-surface Arctic air temperatures, about twice as fast as the global increase (Hansen et al. 2010), is called the Arctic amplification (e.g., Holland and Bitz 2003). Its manifestation in terms of decrease in sea ice coverage provides opportunities, but at the same time new risks are emerging. Using the Northern Sea Route, for example, ships can reduce the distance of their journey between Europe and the North Pacific region by more than 40%. In fact, journeys through the Arctic, which are projected to become increasingly feasible as climate change continues (Smith and Stephenson 2013), could provide an opportunity for cutting greenhouse gas emissions. At the same time, the environmental consequences of disasters in the Arctic, such as oil spills, are likely to be worse than in other regions (Emmerson and Lahn 2012). In order to effectively manage the opportunities and risks associated with climate change, therefore, it is argued that skilful prediction systems tailored to the particularities of the polar regions are needed.

The mounting interest in the polar regions from the general public has also become evident for example from increased levels of tourism in both hemispheres (Hall and Saarinen 2010). The ongoing and projected changes in polar regions and increases in economic activity also lead to concerns for indigenous societies and northern communities. Traditional means of predicting environmental conditions, for example, may become invalid in a changing climate with changing predictor relationships (Holland and Stroeve 2011) and all northern communities are at an increasing risk from accidents such as oil or cargo spills associated with increased economic and transportation activities.

Even though climate change in Antarctica is less apparent than in the Arctic, with the exception of the Antarctic Peninsula and West Antarctica, demand for skilful prediction systems is increasing there too. In the southern polar regions the main stakeholders are the logistics community, which provides essential services to the research community such as flights to and from Antarctica, and tourists and research expeditions, which can encounter extremely harsh conditions (Figure 1)(Powers et al. 2012). It is through the effective running of essential logistical activities, which in turn depend on skilful environmental predictions, that important scientific challenges such as issuing trusworthy projections of future global sea level rise can be addressed.

In the following we will argue that the science of polar environmental prediction is still in its infancy, and that significant progress can be achieved through a concerted international prediction effort, putting the polar regions into focus (see also Eicken 2013).

1. How to improve polar prediction capacity?

Firstly let us turn our attention to the questions of how well existing polar prediction capacity is developed and how progress can be ensured over the coming years. The following discussion will be centred around three research pillars, namely Service-oriented Research, Forecasting System Research and Underpinning Research (see Figure 2). A more comprehensive list of research prorities related to polar prediction is given by PPP Steering Group (2013) and PPP Steering Group (2014).

a. Service-oriented Research

(i) User applications While there is great merit in conducting basic scientific research to better explain fundamental atmosphere-ocean-ice-land processes, the societal value of such knowledge depends on its relevance and application to social, economic, and environmental problems and issues in polar regions. Value accrues through the provision of services, such as weather warnings and ice forecasts, to various users or actors — the individuals, businesses, communities, and agencies that are sensitive to environment-related risks or that manage its effects and consequences.

Service-oriented research, rooted in the social and interdisciplinary sciences, is conducted to understand the decision-making context in which these individuals live and organizations operate, appreciating that exposure, vulnerability, and the capacity to respond to weather and ice hazards are largely driven by many interrelated non-weather factors (e.g., cultural and social practices, international demand and pricing of resource commodities, health status of residents). Such research can inform and direct the design and implementation of weather-related services to enhance their effectiveness leading to improved material outcomes (e.g., safety, mobility, productivity, etc.).

Preparatory research should include reviewing existing and planned research to better define and prioritize potential benefit areas and develop a baseline of current experience, use and perception of services. While presently there is a dearth of social scientific research that explicitly treats the use and value of weather information in polar regions, established programs of study examining adaptation to anthropogenic climate change offer potential opportunities for collaboration on research at the temporal scale of weather-related hazards (e.g., ACIA 2004; Dawson et al. 2014; Lamers et al. 2011; Team and Manderson 2011). This research has identified several unique pressures that contribute to the rationale for making the polar regions a target for the application of improved environmental 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 Panel on Polar Observations, Research and Services (EC PORS) Task Team (available from http://www.wmo.int/pages/prog/www/WIGOS_6_EC_PORS/EC-PORS-3.html).

Among the challenges for service-oriented research is achieving the necessary balance between depth and breadth. For example, intensive community-based research involving interviews and ethnographic techniques is often required to unpack the intricacies of decision-making among residents and leaders. However, the generalizability of findings can be left unaddressed given limited resources (time as much as funding) to conduct parallel work in several communities over multiple years. Other challenges include the limited availability and accessibility to secondary social and economic data; facilitating actor and stakeholder participation, engagement, and partnership within research projects; securing the involvement and coordination of expertise across multiple social science and other disciplines.

(ii) Verification Another important aspect of service-oriented research involves forecast verification. Verification can provide users with information about forecast quality to guide their decision-making procedures, as well as useful feedback to the forecasting community to improve their own systems. Traditionally, forecast verification has focused on weather variables that are of little direct value for most users of weather information, such as the 500 hPa geopotential height. Increasingly though, surface weather parameters like temperature at $2m$ height, wind speed at 10 metre height and precipitation are part of standard verification. The diversity of verification measures has been relatively limited with a strong emphasis on basic statistical measures like root-mean-square error and correlation metrics. Standard verification has moreover mostly concentrated on mid-latitude and tropical regions. Only very recently has the skill of current operational forecasting systems in the polar regions been considered (Bromwich et al. 2005; Jung and Leutbecher 2007; Jung and Matsueda 2014; Bauer et al. 2014). More work will be needed, especially on the verification of near-surface parameters as well as snow and sea ice characteristics (especially drift and deformation).

Some of the biggest challenges in forecast verification relate to the quality and quantity of observations. In fact, representative observational data are the cornerstone of all successful verification activities. Given the notorious sparseness or even complete lack of conventional observations in the polar regions (Figure 3), progress in quantifying and monitoring the skill of weather and environmental forecasts will hinge on the availability of additional observations or better usage of satellite data.

Forecast verification against analyses (which are influenced by the model itself during the data assimilation process) is common practice, because the model introduces spatial and temporal consistency to sparse data and analysis errors are usually much smaller than forecast errors in medium and extended range. This approach can have short-comings in parts of the world, including the polar regions, where the sparseness of high-quality observations and the difficulty of assimilating satellite observations leads to a very strong influence of the models' first guess on the analysis. Enhanced verification in observation space (e.g., satellite data simulators) and increasing analysis quality need high priority.

In recent years, there has been a shift in how verification is perceived. It has been widely recognized that verification activities should focus more strongly on user relevant forecast aspects, that more advanced diagnostic verification techniques are required, and that the usefulness of verification depends on the availability of sufficient high quality observational data. These developments need to be strengthened and promoted in the coming years to advance forecast verification in polar regions.

b. Forecasting System Research

The elements of Forecasting System Research, namely observations, modelling, data assimilation and ensemble forecasting (Figure 2), are no different to those required at lower latitudes. What is important to point out, however, is that there are certain polar-specific aspects that need special consideration in order to enhance predictive capacity—some of these aspects will be highlighted below.

1) OBSERVATIONS

The polar regions are among the most sparsely observed parts of the globe by conventional observing systems such as surface meteorological stations, radiosonde stations, and aircraft reports. Figure 3, which shows conventional observations of different types that were assimilated by ECMWF on 15 April 2015, illustrates the situation: contrast the dense network of surface stations (SYNOPs/blue dots) over Scandinavia with the sparse network over the rest of the Arctic; or compare the coarse but arguably adequate network of radiosonde stations (TEMPs/yellow triangles) over Eurasia with the handful of stations over Antarctica. The polar oceans are also sparsely observed by the Argo array of automated profiling floats (e.g., Roemmich and Gilson 2009), implying challenges in coupled model initialization.

The polar regions are barely sampled by geostationary satellites, but generally have a denser sampling by polar-orbiting satellites, providing the potential for improvements in satellite sounding such as the IASI sounder, or sea ice thickness from CryoSat-2 (Laxon et al. 2013), SMOS (Kaleschke et al. 2012; Tian-Kunze et al. 2013) and Sentinel-1 and the planned ICESat-2 (Kwok 2010; Kern and Spreen 2015). Using satellite-based observations of the polar surface is challenging due to the presence of snow-covered sea ice, which makes it difficult to determine parameters such as ocean surface temperature, surface winds and precipitation. Differentiating between snow and ice-covered surfaces and clouds in the atmosphere has also been a long-running challenge. Making better use of existing and new satellite-based observations is a must for improving forecast initialisation and verification.

Given that observations are key to producing accurate initial conditions and hence forecasts, relatively sparse observational coverage in polar regions may be one explanation as to why the skill of weather forecasts in polar regions is relatively low (see also Jung and Leutbecher 2007; Jung and Matsueda 2014; Bauer et al. 2014). In addition, data assimilation systems are not adequate to optimally exploit the information provided by existing observations, as will be discussed below.

The relative remoteness and harsh environmental conditions of the polar regions are always going to provide a barrier to enhanced observations. With improved technology and power systems the barrier is becoming more of a financial one than a logistical one: improved observations of the polar regions are possible, but are they worth the cost? To answer this, Observing System Experiments (OSEs) are required (see, e.g., Boullot et al. 2014), in which specific observations are withheld (denied) during the data assimilation process, with a particular focus on user-requirements for these regions. To carry out these experiments a sustained observing period is required with significantly enhanced spatial and temporal coverage—a Year of Polar Prediction (see below). In this respect, increasing the frequency of observations from existing stations and vessels (e.g., Inoue et al. 2013; Yamazaki et al. 2015) and adding additional mobile observing systems such as buoys (Inoue et al. 2009; Meredith et al. 2013) would be excellent options. In addition, periods of intense process-focussed field campaigns are required to provide comprehensive observations of processes that are known to be currently poorly represented in coupled models (e.g., Holtslag et al. 2013; Pithan et al. 2014). Furthermore, increased levels of activity in polar regions suggests that additional observations from new voluntary observing platforms may become available in the future. Effectively engaging with stakeholders, therefore, becomes a key element for improving the polar observing system.

2) MODELLING

Numerical models of the atmosphere, ocean, sea ice, snow and land play an increasingly important role in prediction. For example, models are used to carry out short to seasonal range weather and environmental forecasts; they form an important element in every data assimilation scheme;

they serve as a virtual laboratory to carry out experiments devised to understand the functioning of the coupled atmosphere-ocean-sea ice-land system; and they can aid the design of future observing systems (e.g., for satellite missions) through so-called Observing System Simulation Experiments (OSSEs, e.g., Masutani et al. 2010).

Although numerical models have come a long way, even state-of-the-art systems show substantial shortcomings in the representation of certain key processes. For example, skilful model simulations of stable planetary boundary layers and tenuous polar clouds remain elusive (e.g., Sandu et al. 2013; Bromwich et al. 2013). The shallowness of stable planetary boundary layers, layering of low-level clouds, the smaller spatial scale of rotational systems (e.g., polar cyclones) due to the relatively small Rossby radius of deformation along with the presence of steep topographic features in Greenland and Antarctica all suggest that polar predictions will benefit from increased horizontal and vertical resolution (Jung and Rhines 2007; Renfrew et al. 2009; Elvidge et al. 2014). However, while some of the existing problems may be overcome by increased resolution accessible via the projected availability of supercomputing resources during the coming years, it is certain that the parameterizations of polar subgrid-scale processes will remain an important area of research for the foreseeable future (e.g., Holtslag et al. 2013; Vihma et al. 2014).

It is interesting, in this context, to compare the relative importance of different atmospheric processes for different regions (see Bourassa et al. 2013, for a related discussion on turbulent surface fluxes). Vertical profiles of mean initial temperature tendencies due to various dynamical and physical processes obtained from 1-day forecasts with the ECMWF model are shown in Figure 4 for four different regions during boreal winter: the sea ice-free and sea ice-covered Arctic as well as oceanic regions in the Northern Hemisphere mid-latitudes and tropics. Initial temperature tendencies are temporal changes in temperature arising from the governing equations solved by the model directly after initializing the forecasts. Note, that the mean total initial temperature tendency should be close to zero in the absence of model drift (Rodwell and Jung 2008) if averaging is done over a sufficiently large number of cases (Klinker and Sardeshmukh 1992). In the tropics, for example, strong incoming solar radiation together with boundary layer turbulence leads to a heating of lower atmospheric levels, while longwave radiation cools away from the surface. This radiative tendency profile is largely balanced by deep convection, which contributes to effectively removing instability. A similar balance can be found in oceanic regions of middle and high latitudes (Figure 4a,c). However, away from the tropics the importance of dynamical cooling (cold air advection) and boundary layer heating is more pronounced. Radically different heating profiles can be found during boreal winter in ice-covered parts of the Arctic Ocean (Figure 4b): In the free atmosphere, dynamical heating due to the inflow of relatively warm air from lower latitudes is balanced by longwave radiative cooling; in the polar boundary layer the situation is more complex with vertical diffusion playing a significant role as well. The modeled tendencies are the largest in the case of Arctic open ocean and the smallest values are found in the sea ice covered ocean.

Another interesting perspective arises when vertical profiles of the standard deviation of initial temperature tendencies are considered (Figure 5). Large day-to-day changes in dynamical temperature tendencies can be found everywhere. However, it is only in the tropics that the variability associated with the dynamics is matched by that linked to fast convective processes. In middle and high latitudes the situation is more complex with both convection and large-scale precipitation (microphysics) and to a lesser extend radiation playing a role. Again, the ice-covered Arctic Ocean stands out due to the relative lack of fast processes in the free atmosphere. As models have problems properly representing the low-level mixed-phase clouds and shallow boundary layers, there are likely to be larger uncertainties in Figures 4b and 5b than for the other areas. Nevertheless, the above tendency diagnostics highlight the fact that atmospheric regimes in the polar regions can be quite different (ice-covered vs ice-free) and unique (ice-covered parts) as well as radically different to lower latitudes.

A survey of the global forecasting systems used for short-range and medium-range predictions, such as the ones that contribute to TIGGE (THORPEX Interactive Grand Global Ensemble, Bougeault et al. 2010), suggests that many aspects relevant to the polar regions are still missing in existing systems. For example, many centres still use atmospheric-land models only; in these forecasting systems sea ice is persisted throughout the forecast. Obviously these ”weather“ forecasting systems are not tailored to provide predictive information on sea ice characteristics and their future evolution. The expected increase in shipping traffic in the Arctic will require new kinds of forecast products that provide information about sea ice leads, velocity and pressure; these needs can only be met by incorporating dynamic-thermodynamic sea ice models into forecasting systems. Interestingly, existing sea ice models, which were developed with relatively coarse-resolution climate applications in mind, start to show deformation characteristics such as leads when their horizontal resolution is increased (Figure 6). It will be important to assess the realism of these features and explore their predictability. Furthermore, persisting sea ice throughout the forecast may lead to sizeable errors in near-surface variables such as air temperature during periods of strong advances and retreats of the sea ice edge such as in autumn and spring. An example of the mean near-surface temperature difference for October 2011 between forecasting experiments with observed and persistent sea ice field is shown in Figure 7. Evidently, mean differences of up to 4 K after 5 days into the forecast can be found close to the ice edge. Not including coupling between sea ice and atmosphere can result in missing dynamical responses that have consequences beyond the sea ice region, and not just near-surface (Bhatt et al. 2008). While it may be justified for shorter-term prediction in middle latitudes to use atmosphere-only systems, the cryosphere and the ocean need to be explicitly incorporated when it comes to polar prediction (see also, Smith et al. 2013).

Furthermore, there is cleary scope for using regional weather prediction systems in polar regions. These systems offer some advantages compared to global forecast models. For example, polar optimized physics can be used such as for mixed phase clouds and for more comprehensive sea ice specifications (Hines et al. 2015). Furthermore, the use of very high spatial resolution (1 km or so) where non-hydrostatic dynamics becomes important better captures the topographic forcing upon near-surface winds in regions of complex terrain (e.g., Steinhoff et al. 2013). One of the better known regional polar NWP efforts is the Antarctic Mesoscale Prediction System (AMPS, Powers et al. 2012) that telescopes from a 30-km grid covering the Southern Ocean to a 1.1 km nested grid focused on the rugged terrain near Ross Island to support terminal airport forecasts for aircraft coming from New Zealand.

3) DATA ASSIMILATION

In numerical weather prediction, data assimilation systems are used to produce the initial conditions for forecasts. These so-called analyses are based on the numerical model (also used for forecasting, and observations) with an optimization algorithm that combines the two such that a physically plausible estimate is derived that matches the model prediction and observations within their respective error margins (Kalnay 2003). The quality of the analysis is of fundamental importance for forecast skill since forecasting on the time scales considered here is, to a large extent, an initial condition problem. Generally, the sensitivity of forecasts to the analysis changes between short, medium and extended range from smaller-scale and fast processes (e.g., turbulence, clouds, convection) to larger-scale and slow processes (e.g., planetary waves, ocean, snow and sea ice dynamics).

Modern global weather forecasting employs data assimilation systems which use time integrations of the three-dimensional model at 15–25 km resolution and 50–100 vertical levels ($O(10^9)$

grid cells) together with $O(10^7)$ observations resulting in very large numerical optimization problems (e.g., Rabier et al. 2000; Kalnay 2003). Ensemble analysis systems (e.g., Houtekamer and Mitchell 1998) aim at additionally specifying the uncertainty of the analysis that is required for deriving the above mentioned model error margins but also serve as initializations for ensemble forecasts.

Over polar areas, shortcomings in all three main data assimilation components (models, observations and assimilation algorithms) contribute to sub-optimal state estimates (e.g., Jung and Leutbecher 2007; Bauer et al. 2014) leading to a detrimental impact on forecast skill across all time scales. In the atmosphere in which boundary layer processes and atmosphere-surface interaction — particularly with variable sea-ice coverage — are shallow and dominant, the small scale of cyclonic systems (e.g. polar lows) and the interaction of the flow with extremely steep orography are currently not well resolved in global models (and observations), and even less so in data assimilation systems (Tilinina et al. 2014). Observations are sparse and mostly lacking over sea ice and the Antarctic continent. Satellite data are more difficult to interpret due to, for example, little radiative contrast between the surface and atmosphere. The specification of model and observation uncertainty, required to balance the contributions from observations and model in the analysis, is complex because other processes dominate the error budget and spatial error structures are different from those at lower latitudes.

It will be important to address model improvement, observations and data assimilation methods together. In doing so, polar-specific aspects such as the atmosphere-sea ice-ocean interaction and spatial resolution, enhanced surface-based observational networks and satellite data exploitation, assimilation methods more optimally tuned to high-latitude conditions and coupled atmosphere-ocean-sea ice data assimilation at regional and global scales need to be emphasised

4) ENSEMBLE FORECASTING

Ensemble forecasting is an approach to quantify uncertainty of weather or climate forecasts (e.g., Leutbecher and Palmer 2008). The main challenge when designing ensemble prediction systems (EPSs) lies in the proper representation of initial conditions (and their errors) and of model uncertainty to obtain reliable estimates of prediction error and forecast probabilities. Most operational EPSs employ optimal perturbations to represent initial condition uncertainty. Here, optimality refers to perturbations that are designed to ensure their growth, and hence the increase of the ensemble spread, throughout the early stages of the forecasts. In the atmospheric mid-latitudes, baroclinic instability dominates the early stage of forecast error growth (e.g., Buizza and Palmer 1995; Toth and Kalnay 1993); in the tropical atmosphere, on the other hand, convective instability plays the dominant role (e.g., Buizza et al. 1999; Toth and Kalnay 1993). Although it can be anticipated that baroclinic instability has some role to play in the polar regions, research needs to be carried out to identify other more polar-specific sources of perturbation growth—for the atmosphere as well as for other components of the polar climate system such as the ocean and the sea ice.

Given the limitations of existing models in representing some of the key processes in the polar regions, it will be imperative to properly represent model inaccuracy in operational ensemble forecasts from hourly to seasonal time scales and beyond. Different approaches have been suggested including multi-model ensembles and stochastic parameterizations (e.g., Palmer et al. 2005). Most of the existing schemes were developed with non-polar regions in mind, so that it will be important to assess their performance in polar regions taking into account polar-specific aspects, such as the absence of convection in ice-covered regions and the need to describe uncertainty for coupled processes at the interface between atmosphere and land/snow/sea ice. Furthermore, given that routine weather forecasts are likely to be carried out with coupled models by the end of this decade, as they are already used for sub-seasonal and seasonal forecasting, the representation of model uncertainty in sea ice, ocean, land surface, and land-based hydrology will also need to be addressed (see, e.g., Juricke et al. 2014, for first steps in this direction).

In short, it can be argued that with a few exceptions (e.g., Aspelien et al. 2011; Kristiansen et al. 2011) existing work on operational EPSs has focussed on non-polar regions. Because of this, relatively little is known about the quality of ensemble forecasts, including the associated probability forecasts, in polar regions. In fact, a lot of progress in the provision of environmental information can be made by raising awareness of the importance of polar ensemble forecasting, by improving polar-specific aspects in EPSs (e.g., the presence of sea ice) and by applying existing ensemble verification techniques to the polar regions.

c. Underpinning Research

1) PREDICTABILITY AND DIAGNOSTICS

(i) Predictability Predictability research is primarily concerned with the mechanisms that potentially influence forecast skill at different time scales. The predictability of a system is determined by its instabilities and nonlinearities, and by the structure of the imperfections (analysis and model error) in the system (e.g., Palmer et al. 2005). Due to its relative persistence or stability, sea ice anomalies are usually considered a potential source of predictability, especially on sub-seasonal and seasonal time scales (Chevallier and Salas-Mélia 2012; Tietsche et al. 2014; Day et al. 2014). In fact, predictability of Arctic sea ice has attracted considerable atttention in recent years, especially when it comes to predicting sea ice extent anomalies in late summer. Interestingly, there is a large gap between potential predictability estimates of late summer Arctic sea ice extent (e.g., Guemas et al. 2014; Juricke et al. 2014), which provide a relatively optimistic view, and actual

skill which is rather modest (Wang et al. 2013; Stroeve et al. 2014). This highlights the fact that the potential of seasonal to interannual sea ice prediction has not been fully exploited yet and/or potential predictability estimates are overly optimistic due to insufficient representation of the underlying initial and model uncertainties (see, Day et al. 2014, for pointing out the importance of sea ice thickness initialization).

Perhaps because of these shortcomings, statistical forecasts of Arctic sea ice cover currently perform just as well as those performed with dynamical models (Stroeve et al. 2014). This is reminiscent of the case of ENSO forecasting, where even after years of development dynamical models are only marginally more skilful than statistical models at seasonal timescales (Barnston et al. 2012). However, climate change in the Arctic is happening more rapidly than any other region on Earth and there is evidence that these changes could fundamentally affect predictor-predictand relationships in the region, making it difficult to both train and trust such models (Holland and Stroeve 2011). It is therefore imperative for seasonal polar prediction that coupled models improve.

The presence of sea ice, land ice and snow in the polar regions in conjunction with mid-tropospheric inflows of relatively warm air from the mid-latitudes (Figure 4) leads, at times, to the development of shallow and stably stratified planetary boundary layers (PBLs) in the interior of the Arctic and Antarctic during wintertime (Holtslag et al. 2013). The resulting decoupling of the boundary layer from the free atmosphere may have implications for the predictability of the system. On the other hand, extreme temperature contrasts across the ice edge can lead to very unstable PBLs and to turbulent surface heat fluxes in excess of 1000 Wm^{-2} over the adjacent open ocean regions (Papritz et al. 2015). Depending on the dynamical conditions associated with the free tropospheric outflowing air masses, very strong, hurricane-like vortices with diameters typically of a few hundred of kilometres, may develop within a period of a few hours, under the influence of sensible and latent heating from the open ocean (e.g., Rasmussen and Turner 2003; Kristjánsson et al. 2013). These polar lows are responsible for some of the most dangerous weather in the Arctic, due to strong winds, heavy snow fall, and icing on ships and installations. Furthermore, their predictability is highly variable (while some polar lows are very well forecasted, some still come "out of the blue"), because of the fast development over areas with sparse observations, and their small scales. It is also likely that some aspects of model formulations in terms of spatial resolution and parameterized processes are inadequate. Finally, the regions where polar lows strike may change as the Arctic sea ice continues to decline. It is to be expected that the regional vulnerability to polar lows will be even much higher due to these changes, as necessary preparedness may be neglected over areas such as the Kara and Laptev Seas.

From the above discussion, it can be argued that our existing knowledge on predictability, which is primarily obtained from studies in lower latitudes, is not easily transferable due to particular characteristics of the polar regions. Predictability research that focuses on polar regions is therefore urgently needed.

(ii) Diagnostics Forecast error diagnosis is a means to identifying possible weaknesses in the different components of operational forecasting systems. Proper diagnosis, therefore, can help to prioritize research activities in relation to their relative importance.

Substantial progress could be achieved by employing diagnostic methods that have been successfully used in lower latitudes (see Rodwell and Jung 2010, for a more comprehensive discussion). It would be desirable, for example, to identify situations where existing prediction systems have difficulties; backtracking of forecast busts (unusually large forecast errors) throughout the forecast would be one promising approach (Rodwell et al. 2013).

Another promising way forward would be to employ initial tendency diagnostics in polar regions using output from data assimilation systems. By evaluating the initial drift of the model in an NWP context it will be possible to identify possible model weaknesses that result in systematic model error (Rodwell and Palmer 2007; Rodwell and Jung 2008).

2) GLOBAL LINKAGES

Teleconnections between the polar regions and lower latitudes have attracted considerable attention in recent years. In particular, the possible influence of "Arctic Amplification" on the frequency of occurrence of high-impact events over the Northern Hemisphere has been a matter of intensive discussion and controversy (Cohen et al. 2014; Barnes and Screen 2015; Jung et al. 2015). Compared to tropical-extratropical interactions, for which a vast body of literature is available, relatively little is known about the dynamics of polar-lower latitude linkages, especially for the atmosphere. In fact, it could be argued that at present we are at a pre-consensus state (Cohen et al. 2014), not unlike where ENSO research was in the 1970s and early 1980s (Overland et al. 2015; Jung et al. 2015). In order to further our understanding of polar-lower latitude linkages—from their source regions, via atmospheric teleconnections to the places where related chances in weather and climate impact society—it will be important that experts on polar atmospheric processes (i.e., the polar research community) join forces with atmospheric dynamicists traditionally working more on middle latitude phenomena.

It could be argued that further insight could be gained by studying polar-lower latitude linkages also from a prediction perspective. In fact, while teleconnection patterns are well studied phenomena, there is little quantitative knowledge about their role in transferring forecast skill (or uncertainty) from the polar regions into the mid-latitudes and vice versa. Given the relatively poor observational coverage in polar regions (Figure 3), for example, it seems plausible that enhanced observational capacity in polar regions would lead to improved mid-latitude predictions, if polar-lower latitude linkages were sufficiently strong. In fact, recent research indicates that better Arctic predictions will lead to better medium-range and sub-seasonal forecasts in Northern Hemisphere middle latitudes, especially over Eurasia and North America (Jung et al. 2014). Secondly, by considering the interplay between polar and non-polar regions from a prediction perspective on time scales from daily to seasonal, polar-lower-latitude linkages involving relatively fast atmospheric processes could actually be verified. The underlying premise is that the atmospheric processes involved are actually the same across a wide range of time scales (see Palmer et al. 2008, for a more detailed discussion).

In short, it is expected that research on global linkages will enhance our understanding of the role of the polar regions in the global climate system, both in terms of the underlying dynamics and in terms of predictability on time scales from days to seasons and beyond.

2. International cooperation

In order to advance predictive capacity in polar regions, a strong element of coordination will be required. In the following, we introduce two (related) initiatives that provide an international framework through which collaboration between natural and social scientists, operational prediction centres and stakeholders from different nations can be effectively facilitated.

a. Polar Prediction Project (PPP)

The growing need for reliable polar prediction capabilities has been recognized by the WMO when its World Weather Research Programme (WWRP) established the Polar Prediction Project (PPP), as one of three legacy activities of THORPEX. The aim of PPP, a ten-year endeavour (2013–2022), is to *Promote cooperative international research enabling development of improved* *weather and environmental prediction services for the polar regions, on time scales from hours to seasonal.* In order to achieve its goals, PPP enhances international and interdisciplinary collaboration through the development of strong linkages with related initiatives; strengthen linkages between academia, research institutions and operational forecasting centres; promote interactions and communication between research and stakeholders; and foster education and outreach.

Flagship research activities of PPP include (i) advancing sea ice prediction, (ii) understanding polar-lower latitude linkages along with their role in weather and climate prediction and (iii) the Year of Polar Prediction (YOPP)—an intensive observational and modelling period planned for mid-2017 to mid-2019 (see below for details).

PPP is supported through the International Coordination Office (ICO) for Polar Prediction, which is hosted by the Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, in Germany, and informs about, promotes, and coordinates PPP related activities. Further details, including the PPP Implementation Plan (PPP Steering Group 2013), are available from the ICO's website: *http://polarprediction.net*.

b. Year of Polar Prediction (YOPP)

One particularly important international initiative is the Year of Polar Prediction (YOPP). YOPP is a key element of PPP and provides an extended period of coordinated intensive observational and modelling activities, in order to improve prediction capabilities for the Arctic, the Antarctic, and beyond, on a wide range of time scales from hours to seasons, supporting improved weather and climate services, including the Global Framework for Climate Services (GFCS). This concerted effort will be augmented by research into forecast-stakeholder interaction, verification, and a strong educational component. Being focussed on polar prediction rather than a very broad range of activities, YOPP is quite different from the IPY (the International Polar Year 2007–2008). Prediction of sea ice and other key variables such as visibility, wind, and precipitation will be central to YOPP.

Extra observations will be crucial to YOPP in order to test an augmented polar observing system, generate the knowledge necessary to improve the representation of key polar processes in models, and provide ground-truthing that is so important to exploit the full potential of the space-borne satellite network. YOPP will also encourage research, development and employment of innovative systems.

Following the success of the virtual field campaign during the Year of Tropical Convection (YOTC, Moncrieff et al. 2012), YOPP will also have a strong virtual component through support from the numerical modelling community, encompassing high-resolution model simulations that include important polar-specific aspects. Operational model runs will cover time scales from hours to seasons, with a particular focus on sea ice, since for polar regions sea ice is both a critically important environmental variable to be predicted, and a strong modulator of other weather-related predictands across a wide range of time scales.

Output from operational models, including specific additional diagnostics, and dedicated numerical experiments during YOPP will be archived and made available for researchers to better understand strengths and short-comings of existing prediction systems. The new archive will be valuable in itself, even without the planned additional observations that will be assimilated into models. It will certainly help improve process understanding at a detailed level.

Regarding the data strategy, YOPP will take into account lessons learnt from the International Polar Year (IPY). This includes developing a YOPP data portal that builds on the experience of the Global Cryosphere Watch (GCW), including the use of consistent meta data and pointers to other online locations where data can be retrieved. A small number of data centers willing to archive YOPP data (and to support the process) and able to provide digital object identifiers (DOIs) will be identified. Data sets must be open access and, where observations are suited for real-time operational use, submission through the Global Telecommunication System (GTS)/WMO Information System (WIS) should be mandatory. Special attention will be given to WMO standards including the Binary Universal Form for the Representation of meteorological data (BUFR). Finally, all data sets should be published in data journals such as Earth System Science Data (ESSD), and a YOPP special issue in ESSD is desirable.

YOPP will also explore largely uncharted territory in the area of polar forecast verification; it will contribute to our understanding of the value of improved polar prediction capabilities; and it will help to educate the next generation of scientists. YOPP will be carried out in three stages (Fig. 8): the ongoing YOPP Preparation Phase which started in 2013, the YOPP Phase from mid-2017 to mid-2019, and the YOPP Consolidation Phase from mid-2019 to 2023. A more detailed description is available from the YOPP Implementation Plan (PPP Steering Group 2014) and in a meeting report from a high-level planning event — the YOPP Summit — that was held at WMO headquarters from 13–15 July 2015 (Goessling et al. 2015)

3. Discussion

Given the increasing interest in polar regions, it has been argued that existing prediction capacity there needs to be urgently enhanced to effectively manage the risks and opportunties associated with growing human activities and to support local communities in a rapidly changing climate. Research areas with specific activities that have been identified here will need particular attention from the international community of scientists, operational prediction centres and stakeholders to ensure timely progress.

While the focus of the discussion in this paper has been primarily on environmental prediction on daily to seasonal time scales, it is important to point out that by moving polar prediction into the focus of the international community, much needed progress in many areas of climate research and prediction can also be anticipated. In fact, we would argue that the polar regions are ideally suited to a seamless prediction approach (Palmer et al. 2008; Brunet et al. 2010). Firstly, there is no clear distinction between the weather and climate research community in polar regions, with the latter, for example, providing substantial contributions to developing and running the observing system. Secondly, coupled models and coupled data assimilation systems will need to be used, even for short-term predictions traditionally addressed by atmosphere-only systems. While clearly challenging, eventually using coupled models in short-term predictions will provide a unique opportunity for diagnosing the origins of model error and hence improving climate models and climate projections. Furthermore, the high resolution needed for short-term predictions will allow new insights into the climate relevance of small-scale features such as leads in sea ice or orographic jets.

Coupled data assimilation systems will also be important for optimizing the observing system in polar regions. In the past, much emphasis has been put on climate monitoring. With the increasing demand for predictive information, more is asked of the polar observing system; and well-tested coupled data assimilation systems provide a good opportunity to redesign the polar observing system to meet the different competing demands in a cost effective manner. The work will also pave the way for improved reanalysis of the polar regions.

In summary, the growing demand for polar predictive capacity along with a community ready to take on the challenge through international collaboration, means that significant future advances can be expected that go well beyond the polar regions and time scales considered in this paper.

Acknowledgments. Mohamed Dahoui from ECMWF is acknowledged for providing Fig. 3. Soumia Serrar contributed to producing Figs. 4 and 5. Gunnar Spreen and Dimitris Menemenlis provided the original confirguration for the 4-km simulations with the MITgcm that formed the basis for Fig. 6. Contributions to the PPP Trust Fund are acknowledged as well as AWI's financial contribution to hosting the ICO.

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LIST OF FIGURES

FIG. 1. Research icebreaker *Polarstern* on a nocturnal ice station during its winter expedition to Antarctica in 2013. The harsh environmental conditions of the polar regions pose substantial logistical challenges, which call for a concerted international effort to ensure scientific progress. (Photo courtesy of S. Hendricks, AWI)

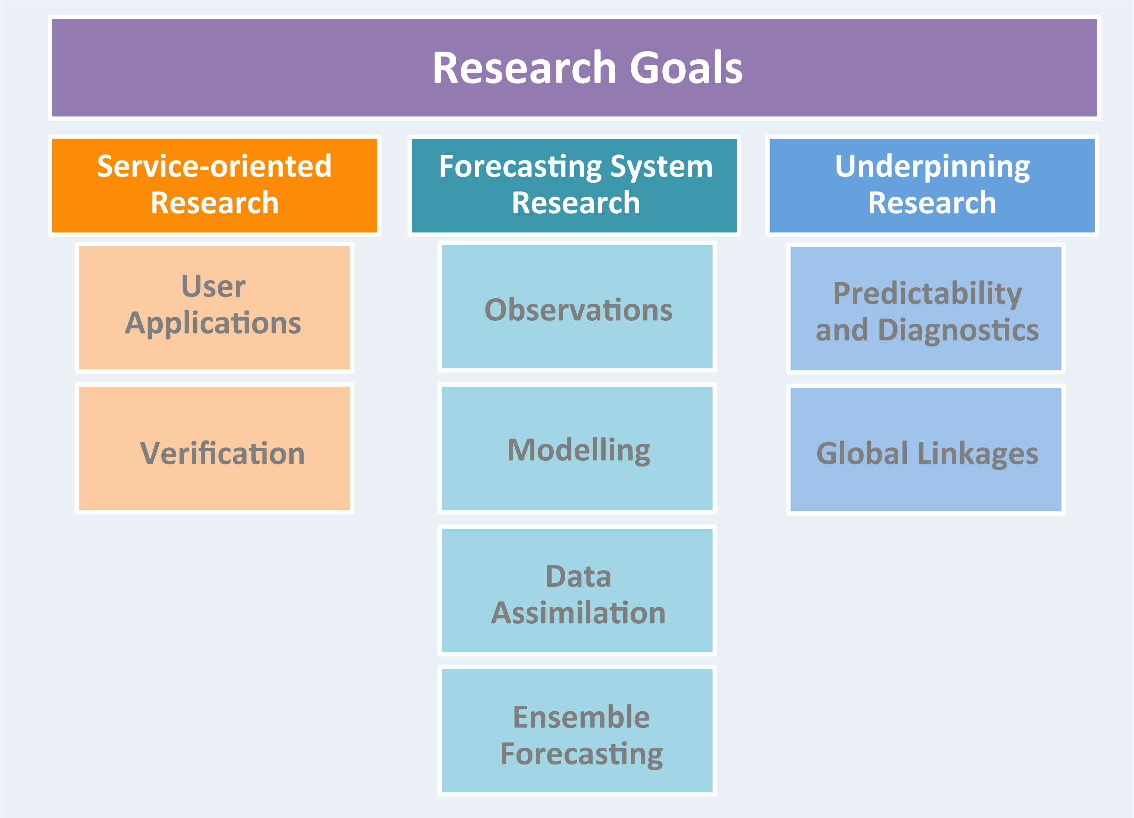


FIG. 2. Research areas that will need to be addressed to advance polar predictive capacity (adapted from PPP Steering Group 2013) .

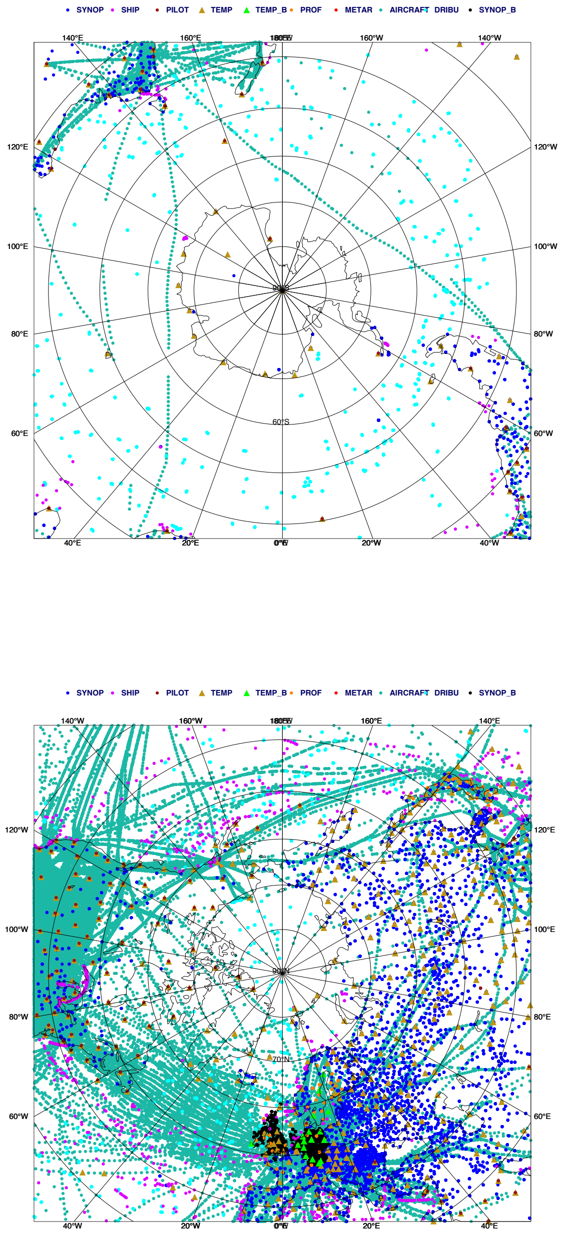


FIG. 3. Conventional observations that were assimilated by the operational forecasting system at ECMWF on 15 April 2015. Different colours are used for different observation types (see legend).

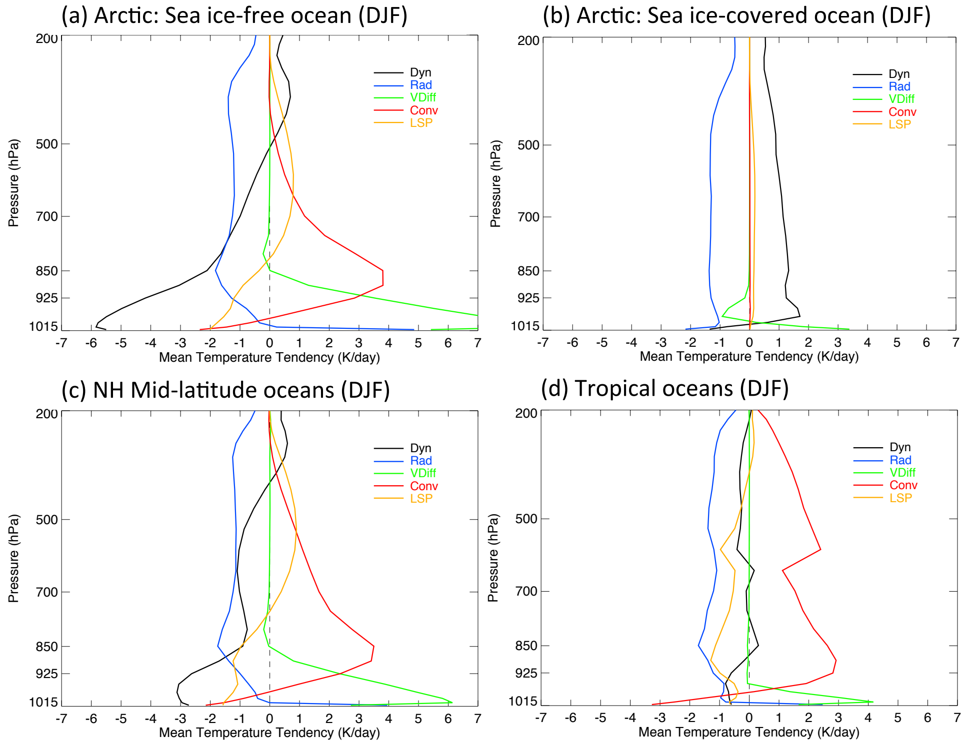
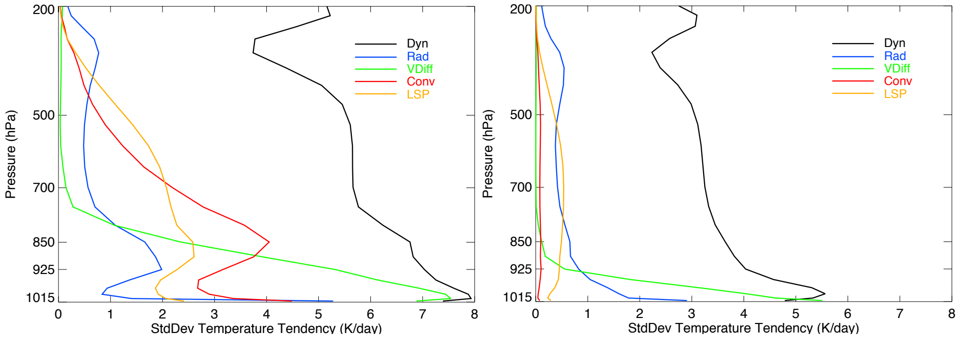
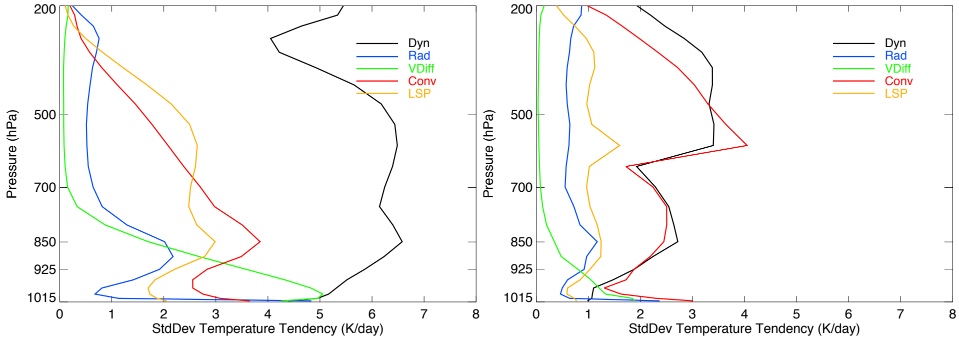


FIG. 4. Vertical profiles of mean 1-day initial tendencies of temperature ($K\,day^{-1}$) averaged over different regions: (a) sea ice-free Arctic ocean, (b) sea ice-covered Arctic ocean, (c) Northern Hemisphere mid-latitude oceans and (d) tropical oceans. Tendencies from the dominant dynamics (black) and physical processes are shown (radiation in blue), vertical diffusion in green, convection in red and large-scale precipitation in yellow. Results are based on weather forecasts during boreal winter with the ECMWF model started every 6 hours during the period December through February from 1979 to 2013.



(a) Arctic: Sea ice-free ocean (DJF)

(b) Arctic: Sea ice-covered ocean (DJF)



(c) NH Mid-latitude oceans (DJF)

(d) Tropical oceans (DJF)

FIG. 5. Same as Figure 4, except for the standard deviation of daily initial temperature tendencies.

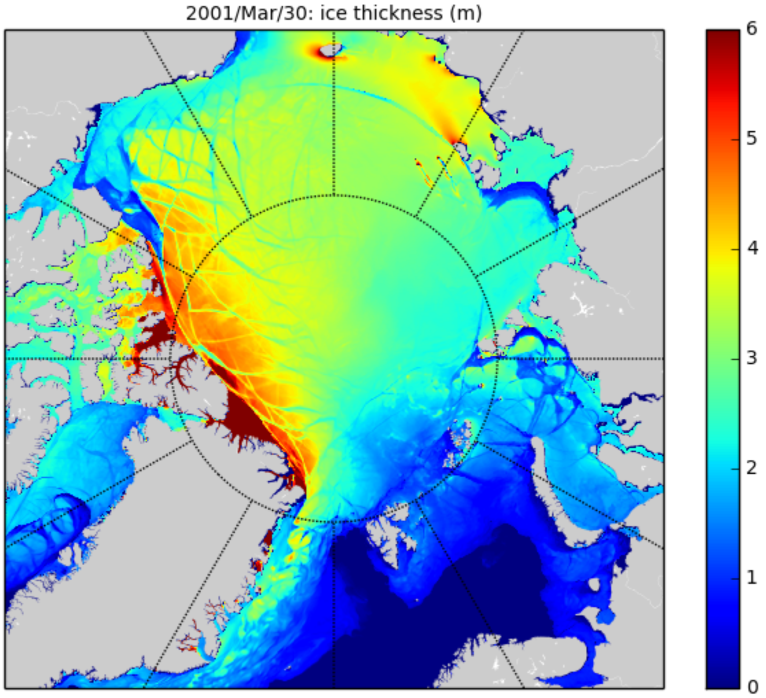
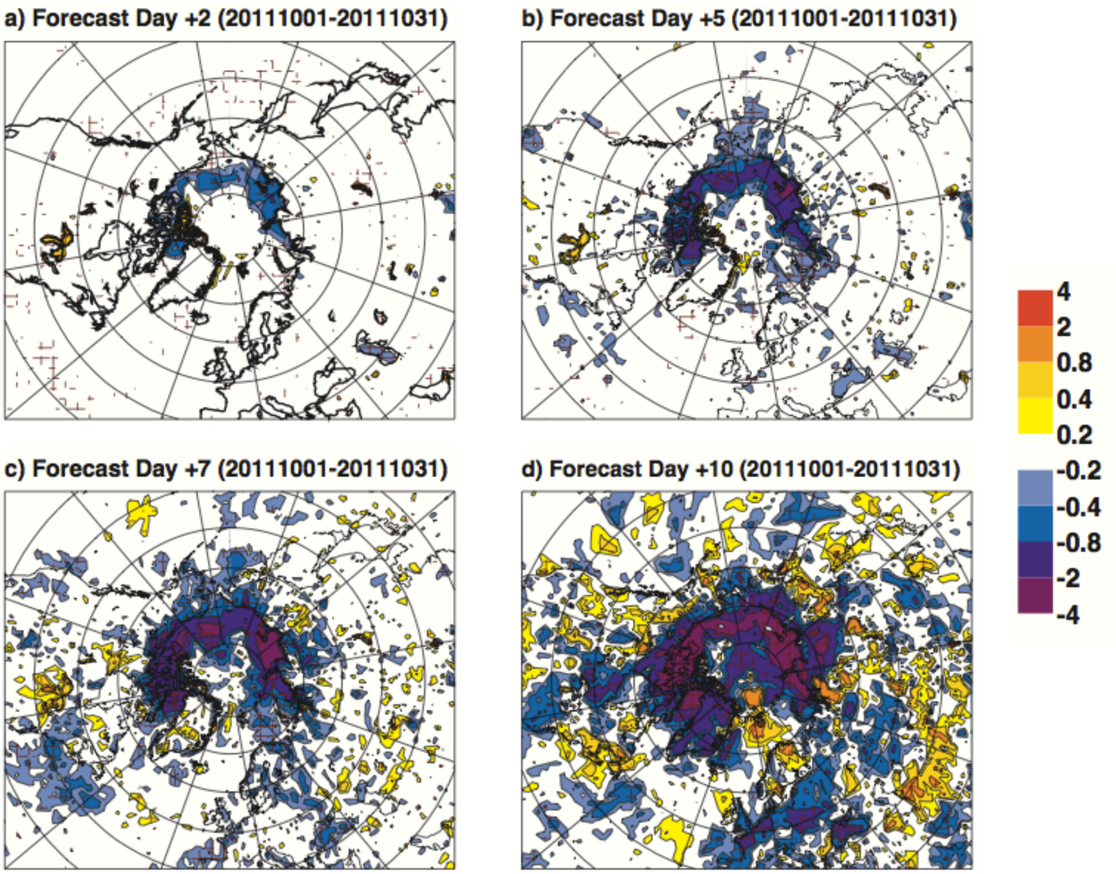


FIG. 6. Sea ice thickness (*m*) on 30 March 2001 as simulated by the MITgcm (sea ice-ocean model forced with reanalysis data) at a horizontal resolution of about 4 *km*. The simulation is very similar to the one described in Nguyen et al. (2012).



830 FIG. 7. Mean 2-m temperature difference (in K) between hindcast experiments using observed and persisted 831 sea-ice and sea surface temperature for October 2011: (a) day-2 (b) day-5, (c) day-7 and (b) day-10 forecasts 832 with the ECMWF forecasting system

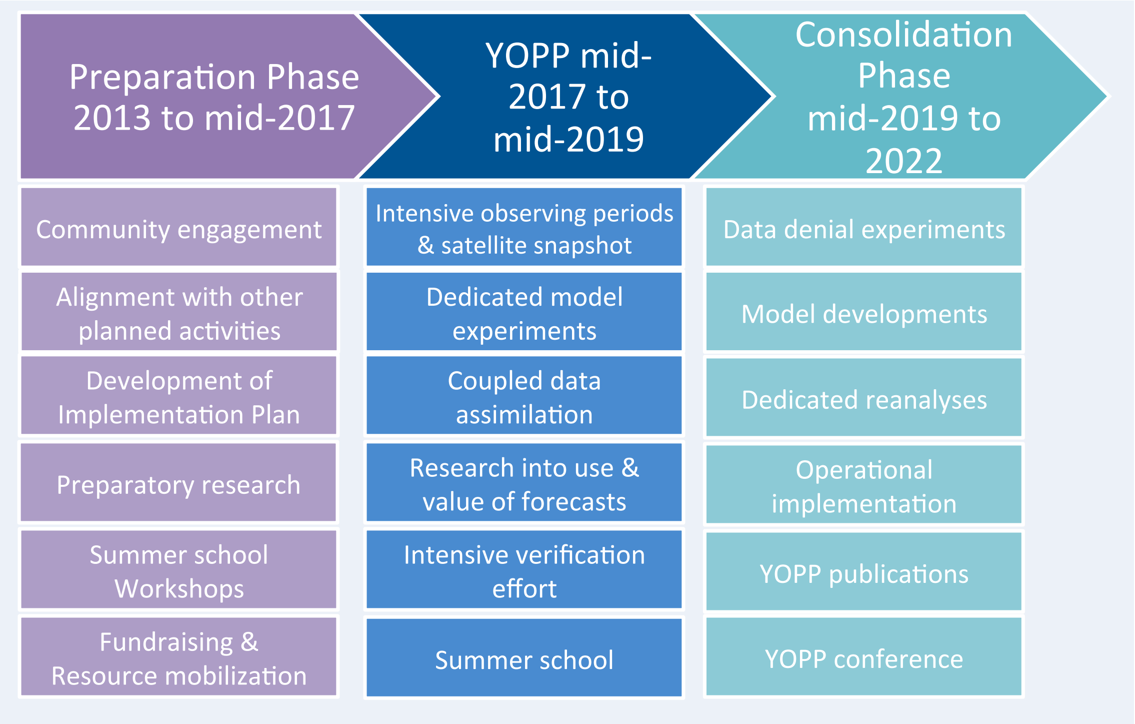


FIG. 8. Three stages of the Year of Polar Prediction (YOPP), including main activities (adapted from PPP Steering Group 2014).