Observational Aspects of the WWRP Polar Prediction Project

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Executive Summary

WMO's World Weather Research Programme is developing plans for a Polar Prediction Project that will promote the improvement of polar prediction capabilities. This will involve advancement of the science in numerical models, data acquisition and assimilation, ensemble forecast methods, verification, and the production of prediction products – all with a polar emphasis. Observations are one key element in this endeavour. 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. The polar oceans are also sparsely observed by the Argo array of automated profiling floats, implying problems in coupled forecasting. The polar regions are barely sampled by geostationary satellites, but generally have a denser sampling by polar-orbiting satellites. Using satellite-based observations of the polar surface is challenging partly due to the ever-changing and highly heterogeneous sea-ice, which prohibits observations of ocean surface temperature and salinity, colour, altimetry/wave height, surface winds, precipitation, etc. Differentiating between snow and ice-covered surfaces and clouds in the atmosphere has also been a long-running challenge.

The relative remoteness and harsh environmental conditions of the polar regions is 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 with a particular focus on user-

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requirements for these regions. To carry out these kinds of experiments a sustained observing and modelling period is planned for 2017-2018 – a Year of Polar Prediction (YOPP). 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 forecasting systems.

1 Introduction

There has been a growing interest in the polar regions in recent years, because of concerns about amplification of anthropogenic climate change. Furthermore, increased economic and transportation activities in polar regions are leading to more demands for sustained and improved availability of integrated observational and predictive weather, climate and water information to support decision-making. However, partly as a result of a strong emphasis of previous international efforts on lower and middle latitudes, many gaps in weather, sub-seasonal and seasonal forecasting in polar regions hamper reliable decision making. Thus, the World Weather Research Programme (WWRP) of the World Meteorological Organization (WMO) is developing plans for a Polar Prediction Project that will promote the institution of a polar prediction system. For more information on the PPP see http://www.wmo.int/pages/prog/arep/wwrp/new/polar_prediction_research_project_main_page.html; this includes the implementation plan that was finalised recently.

1.1 The Polar Prediction Project

The aim of the WWRP Polar Prediction Project (WWRP-PPP) 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." This project constitutes the hours to seasonal research component of the emerging WMO Global Integrated Polar Prediction System (GIPPS). A closely related World Climate Research Programme (WCRP) Polar Climate Predictability Initiative covers GIPPS research on seasonal to decadal time scales. It is anticipated that this prediction system will be based on coupled (atmosphere, ocean, ice, wave) models using an ensemble of repeated model runs to evaluate uncertainty. In this context, 'coupled' means changes in one medium feedback to the other media, principally through interfacial fluxes. Ensembles are generated via error-consistent various on data inputs or plausible variations in physics parameterizations.

In order to meet growing demand for skilful and reliable predictions in polar regions, and beyond, the following eight key research goals have been identified:

- Improve the understanding of the requirements for, and evaluate the benefits of, enhanced prediction information and services in polar regions
- Establish and apply verification methods appropriate for polar regions
- Provide guidance on optimizing polar observing systems, and coordinate additional observations to support modelling and verification

- Improve representation of key processes in models of the polar atmosphere, land, ocean and cryosphere
- Develop data assimilation systems that account for the unique characteristics of polar regions
- Develop and exploit ensemble prediction systems with appropriate representation of initial condition and model uncertainty for polar regions
- Determine predictability and identify key sources of forecast errors in polar regions
- Improve knowledge of two-way linkages between polar and lower latitudes, and their implications for global prediction

In order to achieve the above research goals it is advocated to enhance 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.

It is emphasized that the expected benefits go beyond the time scales (hours to seasonal) and regions (Arctic and Antarctic) considered in the research project. Anticipated improvements in the representation of key polar processes in (coupled) models such as stable boundary layers and sea ice dynamics are expected to reduce systematic errors in climate model integrations and, hence, help narrow uncertainties of regional climate change projections. Furthermore, improved environmental predictions in the polar regions will lead to more precise predictions for non-polar regions due to the existence of global connectivities. To exploit the full potential of this truly "seamless" area of research, it will be mandatory to maintain and develop close ties with the climate research community and that part of the weather prediction community which has traditionally focussed on the non-polar regions.

1.2 Background on Observations

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** – i.e., coupling models that are optimized for uncoupled accuracy at mid-latitudes in a region with low observability and high variability.

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. These relatively high correlations show the skill existing global weather prediction systems in resolving and predicting large-scale atmospheric structures in the day 3-5 day range. 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 Fig. 1 using a 50-day sample from the SHEBA field program. 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, 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. This process will begin explicitly with the inaugural YOPP planning meeting at ECMWF in Reading, UK, in June 2013.

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 validity.

However, data for these ‘calibrations’ are often lacking for polar regions (see Fig. 2, also Matsui et al. 2012). This is a recurrent theme for polar research (see Section 3).

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.

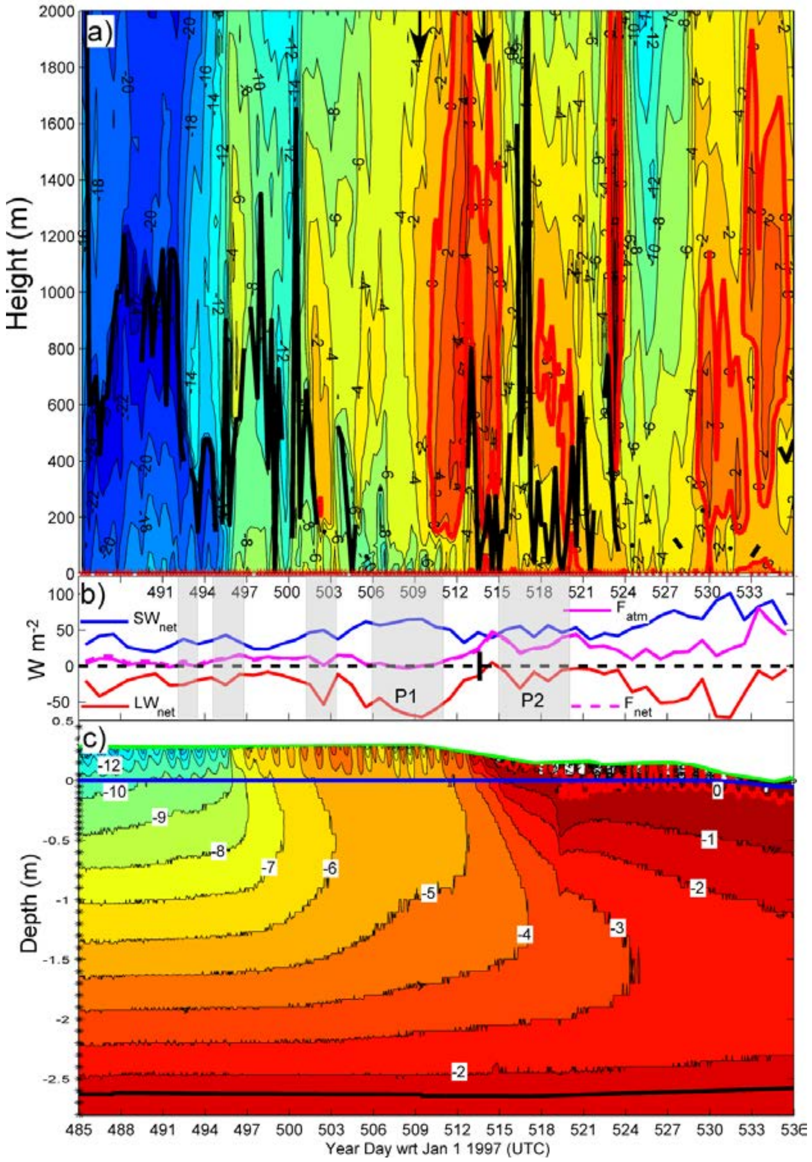

Figure 1: *Temperature in the a) atmosphere and c) snow and ice from April 30 (YD485) to June 20 (YD536), 1998, at SHEBA. Panel b) shows the daily mean net energy fluxes (F is total, SW is solar, and LW is infrared) and the time of melt onset (vertical black bar).*

In a) and c), the 0° C isotherm is shown in bold red and the height of the maximum relative humidity (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).

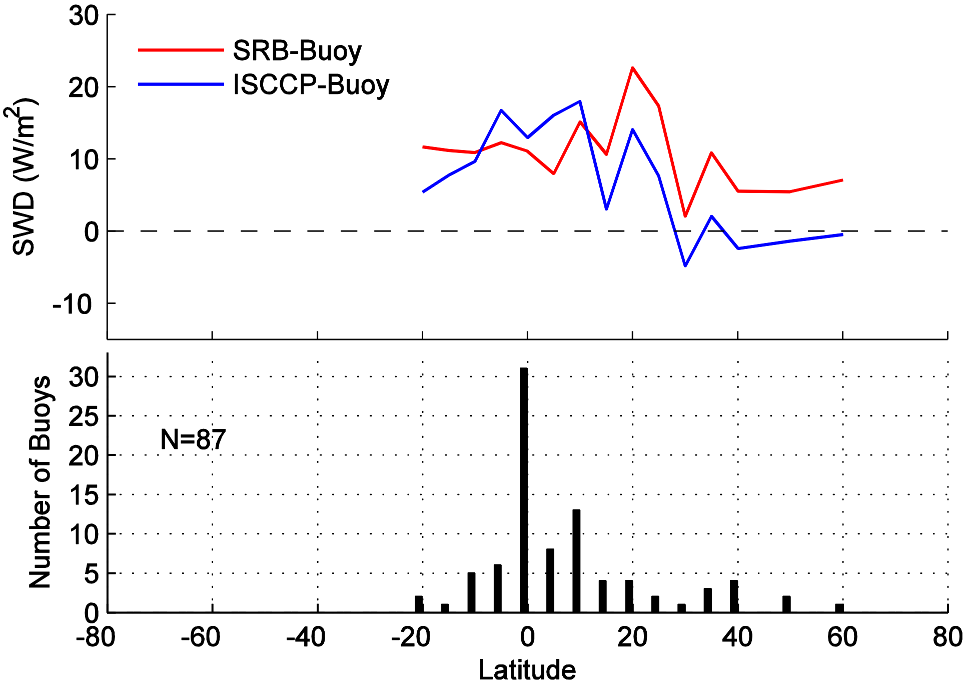

Figure 2: *Differences of mean downward solar radiation satellite products with buoy observations for the last 20 years as a function of latitude: upper panel, mean difference; lower panel, number of buoy sites (Fairall et al. 2012).*

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).

The polar prediction research project will emphasize model development using **existing and planned** observing infrastructure (see Key et al. 2013; Manley et al. 2013;

Mikhalevksy et al. 2013; Scambos et al. 2013). 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).

2 Global Observing System Context

Fig. 3 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. Fig. 3 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 Fig. 3 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).

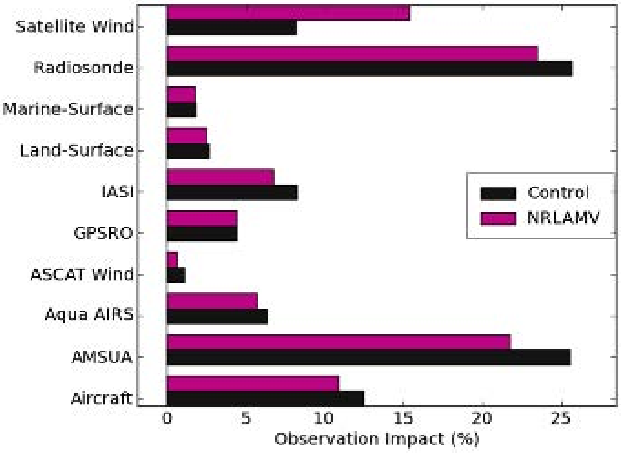

Figure 3: *Fractional observation impacts for forecasts run from December 10, 2010 to January 31, 2011. The control runs (black) made use of the standard GEOS-5 data set, while the NRLAMV runs (magenta) substitute FNMOC AMVs for those normally used in GEOS-5.*

We find similar variable data impacts of **ocean** observing systems on reducing ocean model forecast error. Fig. 4 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-hr forecast error in the Atlantic basin. 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.

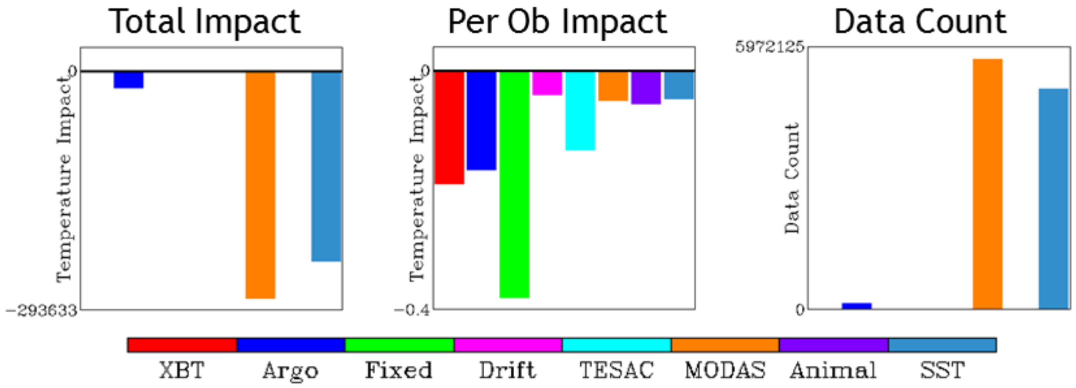

Figure 4: *Histogram plots of impact of temperature data in global HYCOM Atlantic basin domain for October through November 2012. A negative value indicates a beneficial data impact (assimilation of that data type reduced forecast error). Similar results are found for other ocean basins (Indian, Pacific, 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.*

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. (2010) discuss the Antarctic automated weather station program. 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 Fig. 5, 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. (2013) 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).

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.

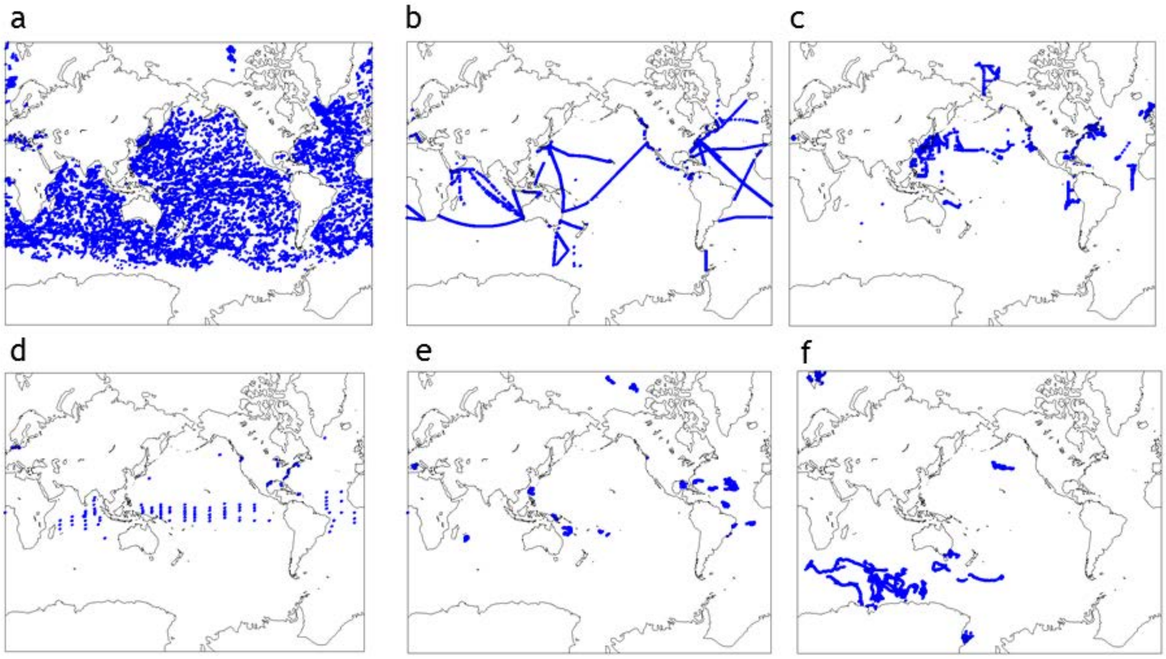

Figure 5: *Data coverage of profiling data types for September through November, 2012. (a) Argo, (b) XBT, (c) TESAC, (d) fixed buoys, (e) drifting buoys with thermistor chains, (f) animal borne sensors. TESAC is a WMO code form and includes CTD and ocean glider observations.*

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 – see Persson et al. 2013), 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 Fig. 6 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.

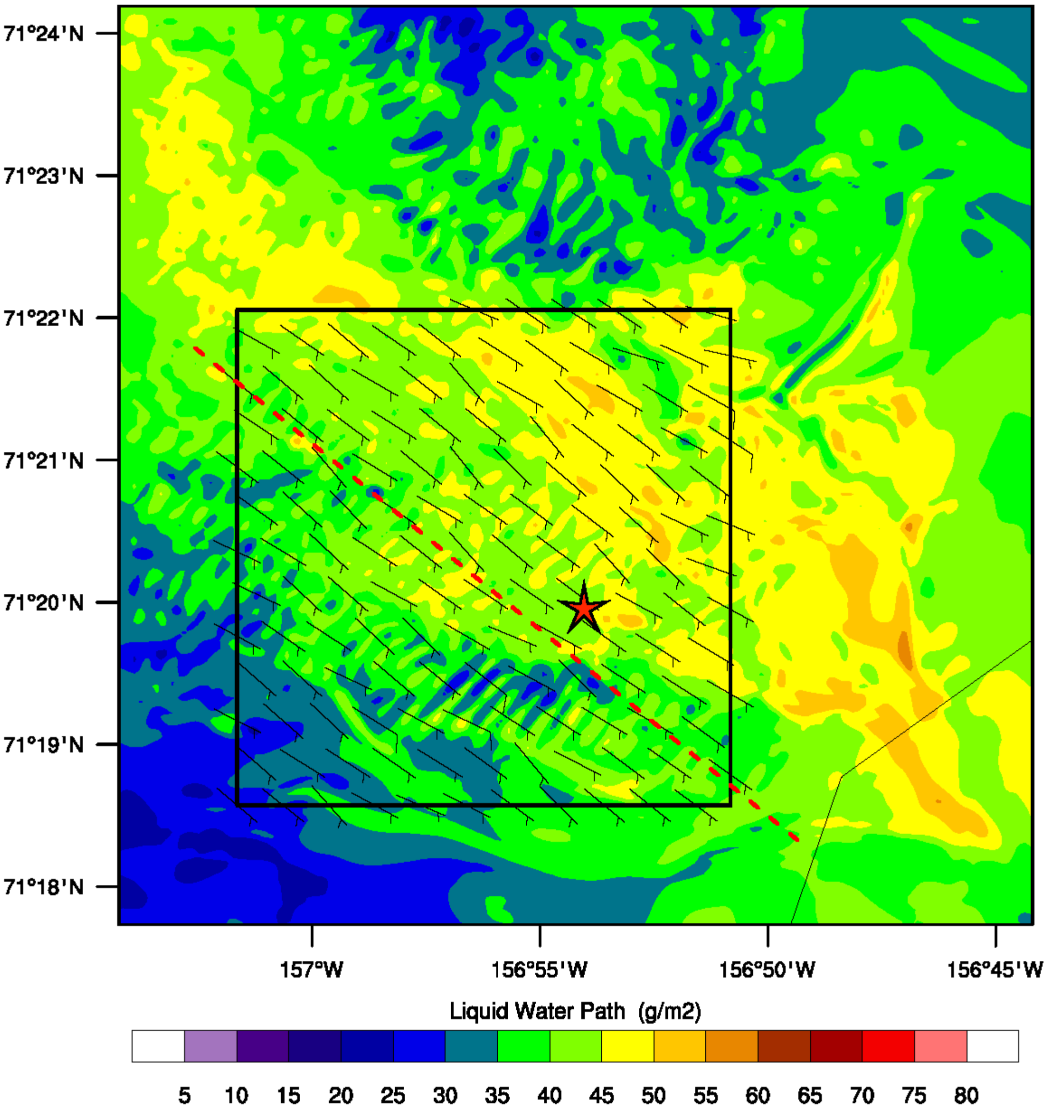

Figure 6: *Liquid water path (colour) and winds (flags) at maximum liquid water level at 2000 GMT on 8 April 2008 for the 50 m nest LES simulation. A half barb on the wind flags indicates 5ms^{-1} and a full barb 10ms^{-1}. The square marks the region used to make total, downdraft, and updraft averages (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. [Solomon et al. 2009]*

4 Key Scientific 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).

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6 Abbreviations

AMV	Atmospheric Motion Vector
Argo	Global array of 3,000 free-drifting profiling floats that measure temperature and salinity of the upper 2000 m of the ocean
CEOP	Coordinated Enhanced Observing Period
CTD	Conductivity, Temperature, Depth
FNMOC	Fleet Numerical Meteorology and Oceanography Center (US Navy)
GAC	Global Area Coverage
GEOS-5	Goddard Earth Observing System Model, Version 5
GIPPS	Global Integrated Polar Prediction System
HYCOM	HYbrid Coordinate Ocean Model
IABP	International Arctic Buoy Programme
IASOA	International Arctic Systems for Observing the Atmosphere
ISCCP	International Satellite Cloud Climatology Project
LAC	Local Area Coverage
LES	Large Eddy Simulation
MODAS	Modular Ocean Data Assimilation System
MOSAiC	Multidisciplinary drifting Observatory for the Study of Arctic Climate
NRL	Naval Research Laboratory (US)
NWP	Numerical Weather Prediction
OSE	Observing System Experiment
OSSE	Observing System Simulation Experiment
PIRATA	Prediction and Research Moored Array in the Atlantic
PPP	Polar Prediction Project
RAMA	**R**esearch Moored **A**rray for African-Asian-Australian **M**onsoon **A**nalysis
SHEBA	Surface Heat Budget of the Arctic
SRB	Surface Radiatioin Budget (satellite observaitions)

SSH	Sea Surface Height
SST	Sea Surface Temperature
TAO/TRITON	Tropical Ocean Atmosphere / Triangle Trans-Ocean Buoy Network
TESAC	TEmperature SAlinity Code
THORPEX	The Observing System Research and Predictability Experiment
TIGGE	THORPEX Interactive Grand Global Ensemble
WCRP	World Climate Research Programme
WMO	World Meteorological Organization
WWRP	World Weather Research Programme
XBT	Expendable Bathythermographs
YOPP	Year of Polar Prediction
YOTC	Year of Tropical Convention