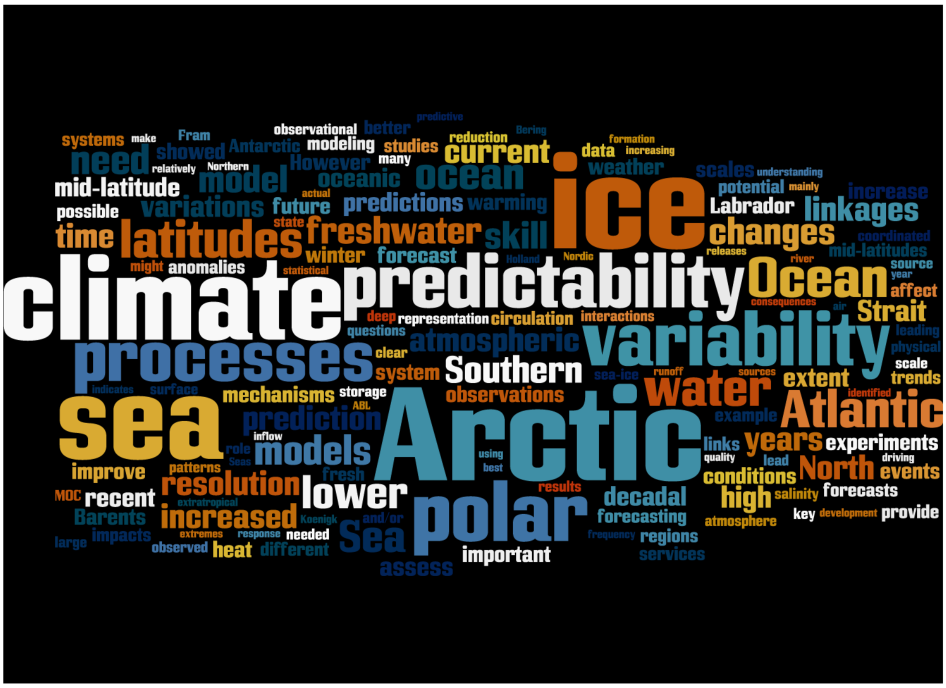

Pre-workshop document for BOG discussions

Ocean processes and mechanisms

Torben Königk, Virginie Guemas, Matthieu Chevallier

Much focus has fallen on polar-mid-latitude direct atmospheric linkages in recent years while the polar oceans have received relatively little attention as a connector. However, the polar oceans have played an important role in dramatic events of the past such as the 'great salinity anomalies' (GSA) of the North Atlantic. Furthermore, changes in the heat storage of the Southern Ocean influence the state at the surface on interannual to multi-decadal timescales and might have an impact on the ocean at lower latitudes. This indicates that skill in predicting important mid-latitude variables could be harnessed from oceanic processes at seasonal-to-decadal timescales.

Some of the general questions to address during this meeting are:

- How important are oceanic processes in linking the polar climate and the climate of the lower latitudes?
- On what time scales do oceanic teleconnections play a key role?

1. Arctic

1.1 Arctic fresh water exchange with lower latitudes

The freshwater input into the Arctic Ocean by river runoff, P-E and inflow through Bering Strait is balanced by outflow of freshwater (liquid and solid) mainly through Fram Strait and the Canadian Archipelago (Dickson et al., 2007; Woodgate and Aagaard, 2005). Freshwater exports out of the Arctic have been identified as an important source for variations of North Atlantic deep water formation. The most prominent example is the formation of the GSA in the Labrador Sea in the beginning of the 1970s (Dickson et al., 1988; Belkin et al., 1998). Large sea ice and liquid fresh water exports through Fram Strait propagated southward in the East Greenland Current and entered the Labrador Sea after about 2 years, leading to a strong and long lasting salinity reduction. The salinity anomalies continued their way under attenuation through the sub polar gyre and reached after about 10 years the Nordic Seas again. Modelling studies (Gerdes and

Köberle, 1999; Haak et al., 2003) were able to reproduce the GSA and showed a long-lasting reduction of deep convection in the Labrador Sea. Results by Deser et al. (2002) and Koenigk et al. (2006) showed that the sea ice extent was increased and the air temperature reduced in the Labrador Sea during GSA-type events. Labrador Sea ice anomalies could further affect the large scale atmospheric circulation (e.g. Alexander et al., 2004; Kvamstö et al., 2004).

The impact of single years with strong fresh water pulses out of the Arctic on the MOC is still debated. Observational time series are too short to settle this debate; modelling results are not consistent (e.g. Häkkinen, 1999; Holland et al., 2001; Jungclaus et al., 2005). However, most models show a clear connection between Labrador Sea convection and MOC at decadal scales, convection leading with a few years (Guemas and Salas-Melia, 2008).

The freshwater storage in the Arctic is mainly concentrated in the Beaufort Gyre and represents about 45,000km^3; a freshwater release of 5% would be sufficient to create a GSA-like event (Proshutinsky et al., 2009). Modelling studies and observations indicate a growing fresh water storage in the Arctic Ocean, mainly due to increased river runoff (Peterson et al., 2002), which will continue to grow in the 21st century (Proshutinsky et al., 2009; Koenigk et al., 2007); the upper ocean freshwater content shows large decadal variations but no clear trends (Polyakov et al., 2008). So far no increase of freshwater export was observed (Rabe et al., 2013). A fresher Arctic Ocean with increased sea level gradient between Arctic and North Atlantic will lead to increased outflow out of the Arctic. Since more and more freshwater is stored in the Arctic, the risk for extreme Arctic freshwater releases might grow in the future with possible consequences for the entire global thermohaline circulation and the mid-latitude climate.

1.2 Heat exchanges between the Arctic and lower latitudes

Measurements of the IPY 2007 showed that the ocean heat flux through Bering Strait in 2007 was at its strongest since 1990 and the Atlantic water entering the Nordic Seas and the Arctic via Barents Sea and Fram Strait was at its warmest for more than 100 years. Woodgate et al. (2010) showed a clear connection between sea ice retreat in summer 2007 and preceding ocean heat flux through Bering Strait.

Many questions regarding time scales and possible tele-connections to the atmosphere are still uncertain. Karcher et al. (2003) used model simulations to show that the warm Atlantic waters enter the Arctic during some particular events. These inflowing warm Atlantic waters spread in too deep depth through the Arctic to affect sea ice directly (Karcher et al., 2011). However, when draining south again into the Nordic Seas this water might slow down the overflow of dense water through Denmark Strait 15 to 25 years later. This could affect the MOC and could provide decadal predictability in lower latitudes. Initialization of such events in model forecasts could enhance the prediction skill. Rudels et al. (2000) argued that the Atlantic water in the Barents Sea penetrates further into the Arctic Basin than the Fram Strait waters. Given the observations by Skagseth et al. (2008) indicating an increasing heat inflow through the Barents Sea, this could alter the predictability connected to the Atlantic water inflow substantially.

The ocean heat transport and water temperatures at the entrance of the Barents Sea provide prediction skill for the following winter ice and atmospheric conditions in Barents Sea and surroundings (Schlichtholz, 2011). Many recent studies showed the importance of Barents Sea ice variations for the mid-latitude climate.

1.3 Relevant questions

- How important is the variability of the exported Atlantic water out of the Arctic for deep water formation and MOC? What is its effect on mid-latitude climate? At what time scales?
- How does increased freshwater input into the Arctic by river runoff, P-E and changes in

melting and freezing of ice affect the Arctic Ocean stratification and circulation? Does Arctic freshwater storage continue to increase in the future or can we expect huge releases out of the Arctic? What would be the consequences and can we predict such releases?
- Which Arctic Ocean processes and interactions with sea ice and atmosphere need to be better represented in current climate models?
- Which coordinated experiments could we propose to narrow down the linkages ice-ocean-atmosphere?
- How realistic are ocean initial conditions taken from ocean reanalysis? What is needed to improve our knowledge of the ocean state and our initial conditions for dynamical prediction?

2. Antarctic

Trends in Antarctic sea ice extent are positive, although with large inter-regional differences. Several different explanations for the sea ice trend have been suggested. These include local trends in surface winds (Holland and Kwok, 2012), positive precipitation trends (Zhang, 2006), subsurface ocean warming (Bintanja et al., 2013), or low-frequency sea ice decadal variability (Polvani and Smith, 2013).

Predictability connected to Southern Ocean processes attracted little attention so far. However, a few recent studies discussed Antarctic predictability. Under perfect-model assumptions, sea ice extent exhibits predictability beyond the year in CCSM3 (Holland et al., 2013). In perfect-model experiments, Zunz et al. (2014) found that the model reproduced well the longer term (10-30 yr), lower frequency variability and trends in Southern Ocean sea ice extent. Boer (2004) and Koenigk et al. (2012) showed high decadal predictability of air temperature in the Southern Ocean. However, the processes leading to this predictability remain unclear. Latif et al. (2006) argued that the multi-decadal variability of SST in the Southern Ocean is anti-correlated with the SST in the North Atlantic.

The inability of current GCMs to simulate the observed variations in Antarctic sea ice extent, even in ocean initialized experiments (Zunz et al., 2013), suggests large room for improvement in the simulation of physical processes and/or in the ocean-sea ice initialization in this hemisphere. The main future tasks are to understand ocean-ice-atmosphere processes and to improve the representation of these processes in the climate models.

2.1 Relevant questions

- Is there any polar climate predictability in the Southern Hemisphere and do polar ocean processes affect Southern Hemisphere mid-latitudes? If yes, what are the processes driving it?
- Which Southern Ocean processes and interactions with the sea ice and the atmosphere need to be better represented in current climate models?
- Which observations do we need to achieve this goal?
- Which coordinated experiments could we propose to evaluate and compare the representation of Southern Ocean processes?
- Which coordinated experiments could be suggested to assess the sensitivity of the mid-latitude climate to the Southern Ocean and sea ice processes?

Atmospheric processes and mechanisms

With input from many participants, compiled by
François Massonnet, Ramiro Saurral, and Thomas Spengler

Linkages between high- and mid-latitudes: Dynamics and physical processes

1) What is the relationship between storm track variability and sea ice and climate variability in the Polar Regions? How can we explain the zonal asymmetries in the observed patterns of change (e.g., the North Atlantic vs. North Pacific)?
2) What is the role and significance of moisture and heat fluxes in modulating sea ice variability and extratropical cyclogenesis? How can we best assess and quantify the transport of latent energy from the extratropics to higher latitudes?
3) What impacts do synoptic and meso-scale phenomena, such as extratropical cyclones, polar lows, or cold air outbreaks have on the climate system in the polar regions?
4) What is the relative importance of different physical components in the high latitude climate system, e.g., sea ice, snow, permafrost, stratosphere, that influence lower-latitude tropospheric variability? Are the identified relationships stationary, transient, linear, non-linear? Are there seasonal differences in the response patterns?
5) Is the mid-latitude atmospheric circulation mostly responding to long-term sea-ice changes, higher-frequency modes of variability (e.g., NAO, PDO, SAM, ENSO), or to short-term (interannual) variability? What is the role of the large-scale oceanic circulation, including potential links between sea ice reduction and MOC variability?
6) Arctic amplification (AA) is a central concept linking high-to-mid latitudes. How well is it quantified? How significantly is it emerging from noise? How are feedbacks (ice-albedo feedback, lapse rate feedback, etc.) interrelated with each other and what is their individual contribution to AA?
7) How much of the observed changes in the Antarctic can be attributed to ozone depletion and/or greenhouse gas increase? What is the relationship between Arctic climate change and variations in albedo?
8) [*Potentially an item also for the predictability BOG*] Have winters really been exceptional in the mid-latitudes in recent years? If so, when will the global warming signal counteract the hypothesized cooling effect of Arctic warming on mid-latitudes in winter?

Data analysis and quality, statistical robustness, and representativeness

1) How appropriate are the statistical methods we are using to assess connections between mid- and high-latitude variability? How representative is the relatively short observational record in high latitudes? Are there pathways to cross- and double-check results? How many (independent, if possible) data sets and models do we need and how many do we have at our disposal to make results as significant and robust as possible?
2) As synoptic-scale extremes (e.g., intense cyclones) are crucial for sea ice depletion (e.g., cyclone of August 2012), are we filtering out potentially important features of the atmospheric variability by using low-frequency bandpass filtering when analyzing data?
3) How many Earth system model (ESM) realizations (ensemble members) do we need, at least, to pretend sampling natural variability correctly?

Observations and model output: Needs and prospects

1) Which kind of field campaigns and what types of measurements do we need? At which frequency and resolution? What kind of diagnostics/metrics do we need to evaluate the proposed linkages? Should we strive to converge to a common vocabulary with clear definitions

of terms, e.g., storm track, jet stream activity and variability?
2) How can we distinguish between plausible mechanisms (as identified in the models) and actual mechanisms (occurring in the real world)?
3) Are our state-of-the-art modeling-systems fit for the purpose to assess linkages between mid- to high-latitude variability? Are our physical parameterizations (e.g., cloud microphysics, surface fluxes, turbulent exchanges) adequately representing the processes relevant for the scientific question of interest and what are the potential shortcomings or inevitable biases?
4) What kind of experimental design and coordinated initiatives do we need to develop to assess the relevant mechanisms, detect potential changes, attribute extremes, and ultimately infer the causal chain between high- and mid-latitude linkages?
5) What level of predictability can we expect from current ESMs? How does the quality of initial ocean/sea-ice/snow/stratosphere/land conditions improve the prediction of mid-latitude variability and extremes?

Prediction and services

Daniela Matei, Javier García-Serrano, Neven Fuĉkar

To obtain a comprehensive understanding of polar weather and climate predictability and predictability of the impacts of polar conditions on lower latitudes requires a global perspective that encompasses two-way atmospheric and oceanic linkages with the lower latitudes across a wide range of time scales. For example, recent research indicates that the decline in Arctic sea ice and enhanced Arctic warming might lead to an increased frequency of occurrence of high-impact weather events over the Northern Hemisphere continents.

At a seasonal-to-interannual time scale, the polar/lower-latitudes linkages are probably established through teleconnection patterns involving the main modes of atmospheric extratropical variability in the respective hemisphere: Northern Annual Mode (NAM) and Southern Annular Mode (SAM). On an even longer time scale (decadal), Arctic-mid-latitudes processes have also been suggested to be a key player in driving the recent global warming hiatus, a phenomenon most evident in Northern Hemisphere winter, or inducing major North Atlantic climate variations such as during the mid 1920s and 1960s events. Poor observational coverage in the Arctic and underdeveloped modeling capabilities, for example, may have a detrimental influence on forecast skill over North America and Eurasia. At the same time, sea ice and Arctic Ocean variations provide an additional source of climate memory and therefore could lead to enhanced extended-range to multi-year predictability in lower latitudes that is likely not fully exploited in existing forecasting systems. A better understanding of the polar-nonpolar links is key to obtain insight where and to what extent future investments in forecast system development in polar regions (e.g. observing system and coupled models) will provide benefit for the prediction of weather and climate in lower latitudes and hence different climate services for sectors such as energy and resource industry, transportation, insurance, fishing and agriculture.

Points on polar predictability

- A more comprehensive evaluation of the levels, sources and errors of predictability for polar regions and their associated impacts across various time scales and seasons, in both observations and models. More case studies are desirable to improve understanding of the mechanisms driving polar (sea ice) changes and to explore untapped predictability sources.
- Multi-year potential skill in predicting monthly mean pan-Arctic sea-ice extent. Actual skill of dynamical forecasts systems is however limited to five months (up to one year for the winter season), with most of the multi-year skill arising from the external radiative forcing. What sets the actual predictability limit?

- More strategies for empirical statistical models for polar climate and sea ice predictions that can be used as reference forecast/benchmark. The empirical and dynamical predictions could be combined to provide better forecast outlooks.
- Initialized prediction systems for polar climate: are the current initialization procedures appropriate? Do we have the necessary observations (observational estimates) for all components (both in terms of quality data and temporal/spatial distribution) and adequate data assimilation techniques to do it? Do we know the required ensemble size? What are the key ingredients that we would like to have in the near term (10 years)? Identify potential needs not captured by the current observing system for enhancing polar predictions.
- Initialization shocks and drifts are routinely seen in seasonal and decadal prediction. Some major assumptions (e.g. stationarity, absence of correlation with the signal) are needed to correct the bias of the forecasts. Are the current bias-correction techniques appropriate and effective for polar predictions?
- Prediction verification: new metrics (regional patterns, more specific quantities) are needed to investigate sea ice and polar forecast skill. The same applies to extending the verification to probabilistic measures, as well as making more extensive use of the available observational data sets/reanalyses. There is a need to assess both sources of predictability and errors as forecast systems increase in complexity and/or resolution.
- Which are the consequences of the relatively low skill in polar weather forecasts and the high uncertainty in polar climate projections?
- Limitations of the current sea-ice modeling capacities. The ley challenges are the transition to multi-category multi-layer sea ice modeling framework, the use of melt pond physics, snow dynamics, a more advanced sea-ice rheology and surface momentum transfer.
- Do we need to make more direct atmospheric boundary layer (ABL) observations all year round? What would improve model representation and prediction of deepening, and warming and destabilization of ABL as a response to sea ice decline? Do we need to advance modeling of ABL via increased vertical resolution, or using more sophisticated sub-grid scale parameterizations or both?

Points on non-polar predictability

- How robust are these polar-lower latitude linkages compared to internally generated variability? How dependent are they on the background climate state?
- Dynamical hindcasts have shown that sea ice anomalies over the eastern Arctic in November represent an actual predictability source for the winter NAO/Euro-Atlantic climate. However, high horizontal resolution in both ocean and atmosphere appears to be required.
- What is the best strategy for increasing model resolution to achieve a more realistic model state and increase weather and climate predictability? For example, increased vertical resolution in the stratosphere could improve the forecasting of changes in the polar vortex and possibly teleconnections between the Arctic and lower latitudes. Also, increasing horizontal resolution is crucial for the realism of ocean-ice-atmosphere interactions and the reduction of systematic model biases, i.e., leading to more accurate forecast impacts of summer Arctic sea-ice retreat. What model parameters should be retuned with increased resolution, or even what parameterizations should be modified or replaced as we increase resolution and resolve more dynamics?
- Global atmospheric experiments prescribing current sea ice trends and/or future projected changes in winter show conflicting results, likely due to the dominance of

internal atmospheric variability.

- Certain non-stationary interactions, such as the Arctic-North Atlantic oceanic linkages, could lead to substantial conditional predictive skill of lower latitudes climate variations at multi-year-to-decadal time scales. For example, the recent accumulation of freshwater in the Beaufort Gyre of the Arctic Ocean, if substantially released to the North Atlantic in response to changing climate conditions, could be a source for a great salinity anomalies, and as a consequence, for an abrupt cooling event of the subpolar gyre.

General points, towards climate services

- Are we appropriately evaluating models and hindcasts to make the best progress?
- Which are the weakest links (critical gaps) in our current prediction systems? Which are the specific high priority issues where progress needs to be made/is feasible in the near future?
- What are weather and climate model elements that could benefit from nonlinear stochastic-dynamics models for the representation of unresolved processes?
- How to assess the value of forecasting system development in the polar/non-polar regions for predictive weather/climate information in decision making? Adaptation of climate predictions for climate services of interest to different stakeholders requires the development of a wide spectrum of different user-guided products. How do we deal with this challenge?
- We need to identify links between predictions of sea ice over the marginal zones and environmental impacts to expand forecasting capabilities towards other disciplines.
- We need to identify links between predictions of sea ice over the marginal zones and requirements of stakeholders and end users (e.g. fishery or delivery companies). This means collecting their needs for the best lead time and target season, the use of probabilistic/deterministic forecast formulation, etc.
- Difference between mean Arctic changes and the regional aspects. It is possible that we do better on global Arctic sea-ice extent changes than on specific regions. Some services may ask for precise (in terms of location) forecasts.

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