A white paper submission to the 2013 Arctic Observing Summit in Vancouver, Canada, April 30-May 2

Understanding Coupled Climate and Weather Processes over the Arctic Ocean: The Need and Plans for Multi-Disciplinary Coordinated Observations on a Drifting Observatory

Ola Persson[1], Matthew Shupe[1], Klaus Dethloff[2], and Michael Tjernström[3]

[1]CIRES/NOAA/PSD, University of Colorado, Boulder, CO USA
[2] Alfred Wegener Institute, Potsdam, Germany
[3] Meteorology Dept., University of Stockholm, Stockholm, Sweden
Corresponding Author: Dr. Ola Persson; ola.persson@colorado.edu

Executive Summary

The climate in the Arctic is changing faster than in other regions. Near surface temperature is rising more than twice as fast as the global average and the perennial sea-ice cover is shrinking fast. The Arctic is on its way to a new climate regime, dominated by first year-ice. At the same time, scientific understanding of processes and feedbacks causing this rapid change is poor, and Arctic regional and global climate and weather modeling remains a challenge. Our understanding is limited by the lack of process-level observations over the Arctic Ocean.

Multi-year, detailed and comprehensive measurements of key atmospheric, sea ice, ocean, biogeochemical, and ecosystem parameters are needed in the central Arctic Basin to provide process-level understanding of the central Arctic climate system, the mechanisms producing the dramatic sea-ice cover changes, and the consequences thereof. Such understanding is necessary for improved modeling of Arctic climate, weather, and ocean conditions; for prediction of the future Arctic sea-ice cover; and for the projection of global impacts. In contrast to most Arctic field programs and since sea-ice forcing is continuous and Lagrangian, year-round measurements following the drifting ice are needed to address many interdisciplinary process interactions in addition to various key disciplinary processes. To obtain these urgently needed observations, a vessel-supported manned drifting station is proposed to be deployed in the sea-ice in the far western Arctic Ocean and proceed through the transpolar drift towards the Fram Strait for 1-2 years. This main observatory will be surrounded by a constellation of manned and/or automated observation platforms to provide needed information on spatial variability and large-scale context. Focused modeling studies will be a key component before, during, and after the field program, which has a target deployment date of autumn 2018. The proposed study is an international, collaborative project between several European Union countries, Russia, and transatlantic partners in the US, Canada, Japan, China, and elsewhere.

While this approach using longer-term drifting observatories may miss some geographically-fixed processes and may be more costly than shorter-term deployments focused on a few disciplinary topics, it will provide a better understanding of the complex Arctic climate system and provide measurements that are more readily useable by the broader scientific and operational community.

The Changing Arctic Climate System

The climate in the Arctic is currently changing faster than in other regions of the Earth. Near surface temperature is rising more than twice as fast as the global average and the perennial sea-ice cover is rapidly shrinking (Fig.1). The Arctic Ocean region is on its way to a new climate regime, the “New Arctic”, dominated by first year-ice and extensive areas of open water in late summer. Estimates have suggested that changes of ~1 W m^{-2} in the net surface energy flux over the past 30 years may be sufficient to account for the observed changes (Kwok and Untersteiner 2011). The scientific understanding of key processes controlling the Arctic climate has always been poor, primarily because necessary process-level observations have been spatially and temporally sparse for logistical and practical reasons.

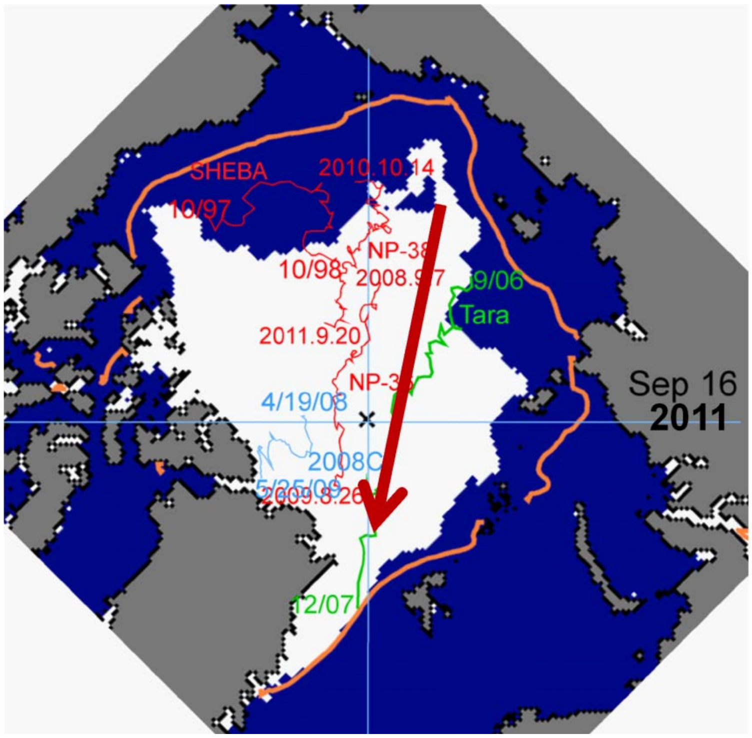


Fig. 1: Reduction of sea ice extent from the median 1979-2000 September extent (pink line) to the September 2011 sea ice extent (white area); drift tracks of some observational campaigns such as SHEBA, two Russian NP stations (NP-36 and NP-38), the French-led Tara expedition, and an automated drifting buoy; and the possible drift track of the MOSAiC drifting observatory (heavy red arrow)(from Shupe et al 2012).

Various studies have focused on possible mechanisms for the change. Most are in agreement that the underlying cause of the changes in the Arctic is the same as that for the globe; that is, the change is due to the accumulation of greenhouse gases in the atmosphere (Solomon et al 2007; Rinke and Dethloff, 2008). Hence, one possible mechanism for the changes in sea ice are direct increases in greenhouse gas (GHG) radiative forcing on the surface, which are estimated to be ~ 1.1 W m^{-2} globally since 1979 (WMO Greenhouse Gas Bulletin Nov 2011). However, the enhanced Arctic warming, the broad nature of observed changes in the Arctic, and the large magnitudes and uncertainties in other mechanisms controlling the surface energy fluxes suggest that the reduction in sea ice cover is likely not due to GHG radiative effects alone. Instead, the observed sea-ice decline is better viewed as a response to a combination of various interdisciplinary processes and regional feedbacks in the coupled ice-ocean-atmosphere system that is being modulated by the growing radiative forcing related to GHG concentrations. Detailed attribution of the ongoing changes is difficult because natural variability in the system is large and may mask the GHG impacts.

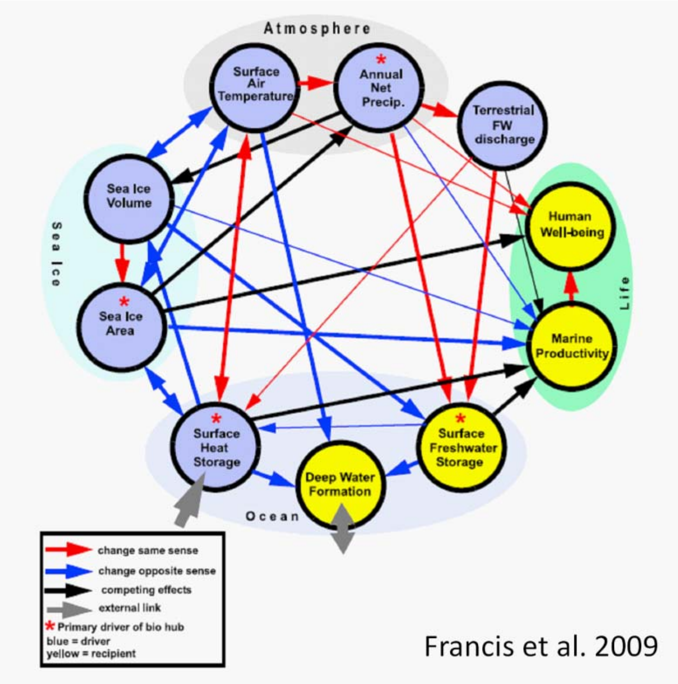
Mechanisms proposed to be directly responsible for the sea-ice changes include a) changes in the atmospheric circulation and the associated enhancement of sea-ice transport out of the Arctic Basin (e.g., Rigor et al 2002, Rigor and Wallace 2004); b) other atmospheric thermodynamic effects, such as enhanced longwave radiative effects from increased meridional atmospheric temperature and/or moisture advection (e.g., Graversen 2006; Graversen et al 2009) or changes in cloud characteristics (e.g., Wang and Key 2005); and c) oceanographic thermodynamic effects, with enhanced energy fluxes from the warmer Atlantic Water (AW) (Polyakov et al 2010, 2011) or Pacific Water (PW) (e.g., Shimada et al 2006) inflows. Effects from these general mechanisms are likely enhanced or suppressed by a variety of feedback processes, such as the ice-albedo (e.g., Curry et al 1996) including differences between multiyear ice (MYI) and first-year ice (FYI), cloud-albedo, aerosol direct/indirect effects, and enhanced meridional transport due to changes in global atmospheric circulation caused by reduction of the Arctic sea ice (e.g., Francis and Vavrus 2012; Jaiser et al. 2012).

Atmospheric radiative fluxes are large in magnitude, with annual mean net longwave and shortwave radiative fluxes over MYI of about -21.5 W m^{-2} and +23.5 W m^{-2}, respectively, (e.g., Maykut 1982; Lindsay 1998; Persson et al 2002; Persson 2012). These fluxes also have significant variability on shorter time scales and therefore contribute a large uncertainty to our understanding of the surface energy budget over sea-ice. A variety of atmospheric and surface processes, such as those related to clouds and atmospheric structure, can potentially produce significant changes in the radiative fluxes, and these processes are currently neither well understood nor well modeled. Additionally, atmospheric turbulent heat fluxes have net annual mean magnitudes of a few watts per square meter, though these also have much greater variability on shorter time scales (factors 10 - 50). Much of these processes and their variability are driven by large-scale atmospheric circulation. Dorn et al. (2012) have shown the strong impacts of changes in atmospheric circulation on the decadal sea-ice retreat using ensemble, coupled regional climate model simulations for 1948-2008. Hence, atmospheric thermodynamic changes and uncertainties can easily account for the estimated change of +1 W m^{-2} required to produce the observed sea ice changes.

Heat fluxes to the underside of the ice from intermediate depth ocean thermal sources (e.g., AW) are generally believed to be ~3 W m^{-2} or less, though it is hypothesized that these magnitudes may be larger in some geographically fixed locations (e.g., Polyakov et al 2011). Though the current magnitudes of the ocean heat fluxes to the bottom of the sea ice from these intermediate warm waters are significantly smaller than those from atmospheric radiative fluxes, the heat potentially available in this AW only a few hundred meters below the sea ice is enormous; hence, understanding ocean vertical mixing processes are important for assessing both current and possible future impacts on the sea ice from this heat source (e.g., Proshutinsky et al. 2012). Uncertainties in Arctic Ocean circulation trajectories of both AW and PW also exist, since these are forced by near-surface atmospheric wind and thermal impacts which are not well monitored (Proshutinsky et al. 2012). Oceanic heat fluxes from local heating of the ocean mixed layer by solar radiation in leads and open water near the ice edge and through solar transmission through the sea ice is a potentially strong positive feedback mechanism on the melting sea ice, especially in the marginal ice zone in late summer through autumn (e.g., Kay et al 2008; Steele et al 2010). Moreover, this process is changing as the balance of FYI versus MYI is changing. Hence, it is currently a major topic of research that involves not only ocean heat storage and stability but considerations of atmospheric radiation, impacts of storms on turbulent heat flux release (e.g., Inoue and Hori 2011; Long and Perrie 2012), ice optical characteristics, snow cover, and biogeochemical impacts on ocean solar absorption.

Within each discipline, numerous processes are involved in each mechanism. Furthermore, many of the processes involve interdisciplinary process interactions, further complicating the understanding of the system. There is an evolving recognition that interdisciplinary process interactions are significant in the Arctic climate system (Fig. 2), and that these interactions not only complicate the understanding of the current climate but may also provide complex interdisciplinary feedbacks as the climate changes. Therefore, the scientific understanding of processes and feedbacks associated with this rapid change is especially poor, since our knowledge of the key processes is incomplete, the relative roles of these processes may be changing as the climate changes, strong interdisciplinary interactions are complicating the processes, and data sets previously collected for model and satellite validation may not adequately represent the current conditions of the "New Arctic". Hence, climate, ocean, and ecosystem modeling and improved weather and sea-ice forecasting in the Arctic remains challenging.

Kwok and Untersteiner (2011) outline some of the unquantified sea-ice and cryospheric processes possibly affecting the sea ice change. These include uncertainties associated with sea-ice dynamics, ice-ocean heat storage and fluxes, changes in snowfall and melt-water runoff, and melt pond formation. Other key interactive processes and feedbacks include different radiative properties of FYI compared to MYI; an ice-loss induced increase of Arctic Basin storm activity possibly enhancing the decrease of sea ice in the marginal ice zone through mechanical or thermodynamic effects (Asplin et al. 2012; Kwok and Untersteiner 2011); possible changes in the known large impacts of cloud microphysical characteristics (especially cloud phase) on surface radiative fluxes and temperature (e.g., Persson et al. 1999; Intrieri et al. 2002;



Francis et al. 2009

Fig. 2: Anticipated relationships and interactions between various characteristics and processes in the atmosphere, sea ice, ocean, and biology (including human activity) as the climate changes (from Francis et al 2009b).

Shupe and Intrieri 2004; Solomon et al. 2009; Stramler et al. 2011; Klaus et al. 2012), local production of cloud condensation and/or ice nuclei from lead biological sources affecting the radiative properties of Arctic clouds (Leck and Bigg 2007; Orellana et al 2011), and others. Uncertainties in cloud processes and how they may be changing are of particular concern because of the large associated radiative fluxes and thus their potential for significant surface radiative impacts. It is likely that a combination of these or other atmospheric, cryospheric, oceanographic, and biological processes are triggering or enhancing the observed changes, though their relative magnitudes are unknown.

The static stability of the upper Arctic Ocean is also changing through increased freshwater from the melting of sea-ice and river runoff in addition to increased solar heating. However, the sources and sinks of Arctic Ocean freshwater are not well quantified, so observations and year-round monitoring of surface freshwater fluxes and ocean salinity are sorely needed in the central Arctic basin (Proshutinsky et al 2005). The increasing late-season heat absorption by the upper ocean and the changing freshwater content may also impact the vertical mixing in the upper ocean during the winter, which is a critical process for distribution of nutrients and primary biological production (Proshutinsky et al. 2012; Popova et al. 2012).

Autumn oceanic heat fluxes have also been implicated in the modification of the regional atmosphere and in impacting the subsequent northern hemispheric circulation (Francis et al 2009a; Overland and Wang 2010; Francis and Vavrus 2012). As shown by Jaiser et al. (2012), the enhanced summer sea ice retreat triggers, via amplified baroclinic Arctic systems, a large-scale barotropic response in the winter atmosphere, with a shift toward stronger meridional flow and a more negative phase of the Arctic Oscillation in mid-latitudes. Hence, quantifying and understanding these ocean heat fluxes are important for mid-latitude weather and climate prediction.

Therefore, multi-year, detailed and comprehensive measurements, extending from the ocean through the sea-ice and into the atmosphere, are needed in the central Arctic Basin to provide process-level understanding of the Arctic climate and weather system and how it is changing. These are necessary for improved modeling of Arctic climate and weather conditions, for prediction of the future Arctic sea-ice cover, and for prediction of the impacts of the evolving Arctic climate on the global climate.

Past and Current Measurement Programs

The scientific community has long recognized the need to understand Arctic physical processes, partly to understand the Arctic climate and weather system and partly to understand its role in the global climate. Because of the logistical difficulties in accessing the Arctic and maintaining measurements in severe environmental conditions, process-level measurements throughout the atmosphere, sea-ice, and ocean have been difficult to obtain, especially over the Arctic Ocean. Early scientific expeditions, such as those of Nansen and Amundsen, provided initial glimpses of atmospheric, cryospheric, and oceanographic structures and processes, including some of the basic interdisciplinary interactions, though the process-level understanding was limited by available technology. A few long-term atmospheric data sets, such as those collected by the Soviet North Pole drifting stations, provide some descriptive climatological basis. Again, the parameters measured were limited because of the limited available technology, the primary operational purpose of the measurements, and the lack of motivation for measuring the interdisciplinary process interactions.

Recent expeditions and deployments of automated stations or buoys have typically focused on individual physical processes, often ones specific to the ocean, cryosphere, atmosphere, or biosphere. Very few provide measurements that permit the simultaneous analysis of key interdisciplinary processes, and hence these process interactions are not well observed or understood. In attempts to include interdisciplinary linkages, some oceanographic and/or cryospheric studies rely on atmospheric models or reanalyses, with researchers either willing to accept or not recognizing that errors in such data are large enough to overwhelm signals from the processes being studied. Additionally, such model-assisted data sets do not include many of the feedbacks present in the real world. Atmospheric reanalyses, which assimilate the few available observations into model first-guess fields, primarily represent model output over the Arctic Ocean due to a dearth of regional observations. Since forcing-term parameters such as energy and momentum fluxes are neither observed nor assimilated, these parameters are entirely dependent on the model parameterizations. Hence, the significant errors present in most models for such parameters (Fig. 3) are also present in reanalysis output (e.g., Tjernström et al 2008; Walsh et al 2009; Inoue et al 2011). For instance, clouds, which are present 50-90% of the time over the Arctic Ocean, depending on the season, are particularly poorly represented in models, leading to errors of several tens of watts per square meter in the surface radiative fluxes (Fig. 3). Such errors, if present as biases, can overwhelm the net annual surface energy flux, which is typically less than 10 W m^{-2}, and are clearly larger than the 1 W m^{-2} estimated to have caused the current change in sea-ice conditions.

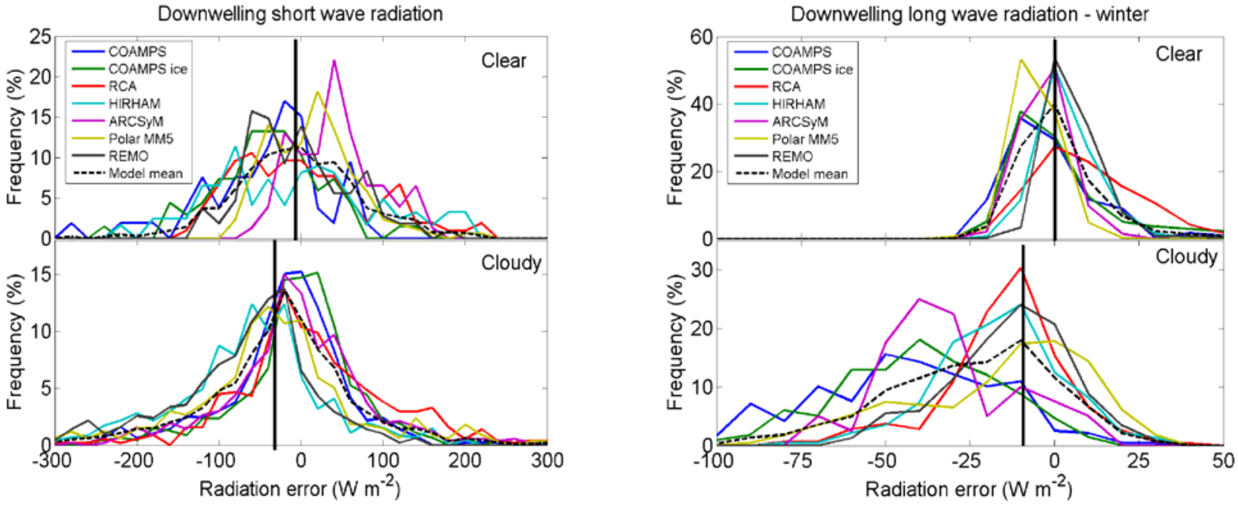


Fig. 3: Validation of prominent regional climate models using the year-long SHEBA hourly surface shortwave and longwave radiative fluxes for clear and cloudy conditions (Tjernström et al 2008). Significant surface radiation biases are observed under cloudy conditions.

Most observational campaigns have also been limited to short periods of a few months or less. They have been restricted to periods of the year when accessibility and instrument deployment is easier, spring through late summer, and focused on specific regions dictated either by accessibility or the locale of a specific process. The brevity of these campaigns is also often determined by limited resources. However, processes in the atmosphere and ocean that affect the sea ice occur throughout the year and throughout the Arctic Basin, generally vary over the annual cycle, and have significant variability on even smaller temporal scales (Fig. 4). That is, the mass and energy fluxes forcing the sea-ice, on a broad range of spatial and temporal scales, are integrated throughout the year and over the locations transited by each floe, producing the net changes to the sea ice. Since there are various geographically-fixed forcing processes, the trajectory of each individual ice floe through the Arctic Basin can impact the net forcing it experiences. This may be especially true for forcing from the ocean related to bathymetry and circulation patterns. Atmospheric forcing may be less dependent on geographic location, though it is unknown whether there are regional variations for some types of forcing, such as precipitation, winds or even surface radiation. Hence, to understand the processes impacting the sea ice over its full life cycle, measurements need to be made of formation, growth,

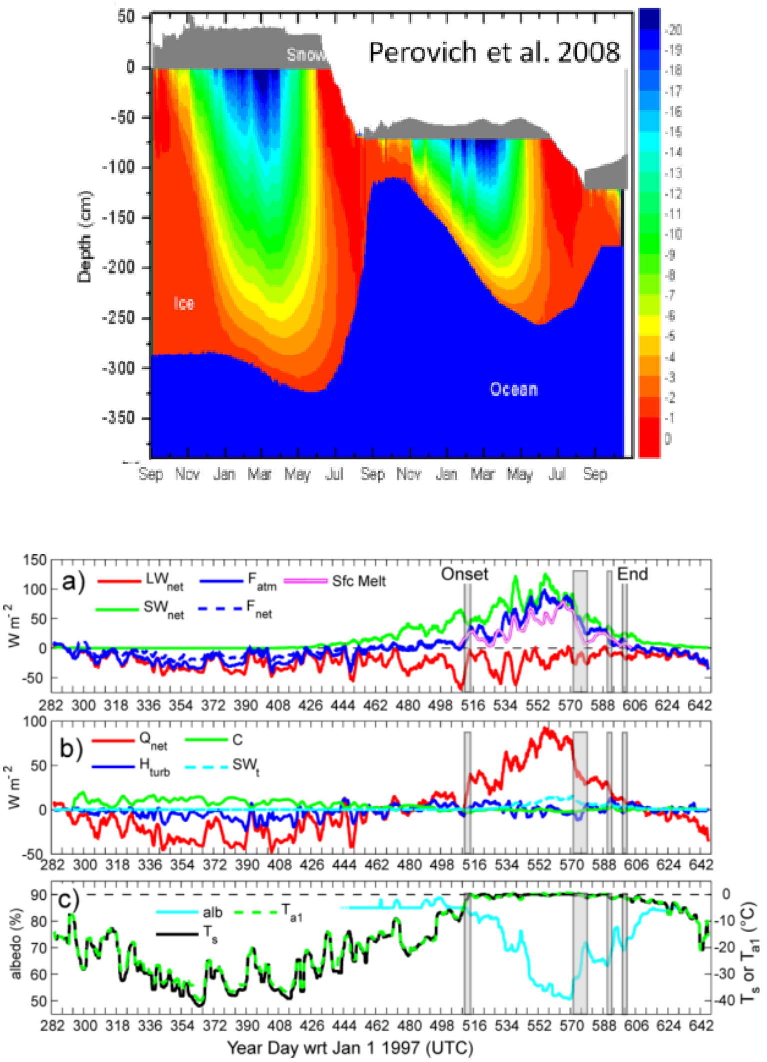


Fig. 4: Observations illustrating the annual cycle of the sea-ice structure and the atmospheric energetic forcing. ***top:*** *Measurements of internal ice temperature, ice thickness (top and bottom), and snow depth through two annual cycles of an Arctic multi-year ice floe (Perovich et al 2008). The bottom growth and top/bottom melt of the sea ice, its different thermal characteristics, and the implied effects of the varying snow depth all illustrate seasonally varying atmospheric, cryospheric, and oceanographic processes impacting the sea ice.*
bottom*: Annual cycle of surface energy flux components, surface temperature, albedo, and near-surface temperature during the SHEBA drift. The grey areas show transitions related to the onset and end of the summer melt. The different summer and winter processes are illustrated by the seasonally changing variability characteristics of the surface temperature, and the seasonally differing magnitudes and sign of the radiative and turbulent heat fluxes. (Persson 2012).*

transport/deformation, melt/decay/export periods, ideally for a wide variety of ice types and locations. Measuring one or a few processes during a short period of time, while perhaps providing useful information specific to that process, does not demonstrate the significance of that process relative to the other forcing received by the floe at other times of the year.

Only a few measurement campaigns have attempted to make year-round measurements over the sea ice. These include the Fram expedition by Nansen (1893-1896) (Mohn 1905), the Soviet (1937-1991)/Russian (2003-present) drifting stations (Lampert et al. 2012), the Surface Heat Budget of the Arctic Ocean (SHEBA; 1997-1998) (e.g., Perovich et al. 1999), and the French Tara expedition (2006-2007) (e.g., Vihma et al. 2008; Bottenheim et al. 2009) (see Fig. 1). While data from all of these expeditions have been valuable for promoting our understanding of the processes affecting the sea ice, all of these campaigns had significant limitations to the parameters measured. Arguably, SHEBA has provided the most broadly useful multi-disciplinary data set, though the latest Russian drifting stations are now including many more measurements allowing the exploration of more interdisciplinary interactions. The SHEBA observations were geographically limited to the Beaufort and Chukchi Seas, occurred on multi-year ice in a region that is now almost entirely first-year ice and late-summer open water, and occurred at the end of the "old Arctic" just before the rapid changes that have occurred over the last 10-15 years.

Observational campaigns using automated sensors have also been used and continue to be used. Successful automated observational deployments include tethered oceanographic buoys that have obtained long time series of temperatures and currents in key regions, such as along the Eurasian continental shelf, near the Fram Strait, in the Beaufort and Chukchi Seas, and at the North Pole (e.g., Polyakov 2011). Ice mass-balance buoys are able to obtain crucial snow and ice thickness measurements for about 1 year on individual ice floes (e.g., Morison et al. 2006). New suites of ice and ocean buoys may provide more ocean and ice parameters and greater reliability. Some are attempting to acquire automated measurements from the atmosphere through the ice into the ocean [e.g., French IAOOS Project (http://www.iaoos-equipex.upmc.fr/)], including sampling some of the optical atmospheric properties. However, automated sensors deployed on buoys generally provide very limited parameters and are often destroyed or ejected by sea-ice movements; those parameters that are successfully measured typically only provide one or a few descriptive parameters, and are not sufficient to understand the physical processes and process interactions. Automated underwater vehicles (AUVs) are now able to provide useful oceanographic measurements during some campaigns, while automated atmospheric measurements with unattended airborne vehicles (UAVs) have only successfully measured a few parameters in limited campaigns near the coast of the Arctic Ocean.

While satellite retrievals provide very useful spatial descriptions of some parameters, the accuracy and/or vertical positioning and resolution of many parameters are limited by the environmental conditions (e.g., clouds, thermal height ambiguity). Crucial atmospheric measurements, especially surface radiative and turbulent fluxes, boundary-layer and free troposphere thermal and kinematic profiles, and cloud macro and microphysical parameters, have been notoriously difficult to measure with the necessary accuracy from either satellite remote sensing or surface automated systems. Also, because of the transient nature of the atmospheric structures and hence the need for continuous long-term measurements over extensive areas to establish a climatology, sporadic measurements with airborne in-situ systems (either manned or unmanned) can only provide glimpses of the atmospheric structures. Only frequent, long-term dedicated measurements of this kind can provide the needed climatological description of the Arctic atmospheric structure. These techniques all have potential for providing some of the needed data for understanding the Arctic climate and weather system, so further development of satellite retrieval techniques, surface-based automated measurements systems, and unmanned airborne or underwater mobile measurement systems is clearly warranted. However, currently, these techniques are not extensive enough in parameters measured, are unable to adequately resolve the vertical and horizontal atmospheric structure, and do not provide the necessary accuracy for most of the parameters measured.

Motivation for New Comprehensive Arctic Measurements

As described above, the fast-changing Arctic climate system poses major challenges for understanding and modeling a system that is poorly understood even at the outset. To study this system at a level sufficient to understand and model the present changes and meet societal expectations requires new, enhanced, and coordinated measurements in the central Arctic. The motivation for such measurements is clear:

- Models are critical for understanding climate and climate change. However, current numerical weather and climate models have significant problems in reproducing the current state and are unable to describe observed system interactions. Additionally, these models will likely also be unable to characterize significant shifts in processes or the appearance of new processes as the Arctic continues to change. There is therefore a need for observations to constrain new process-based model parameterizations for improving the basic tools for prediction of weather and sea-ice conditions, as well as for climate projections.
- Arctic change has important implications for resource development, transportation, and commerce, thus increasing the need for science-based guidance on large-scale circulation impacts, ecosystem changes, new climate states, and commercial interests.
- Observational programs over the past 20 years have all been limited in important ways. Few were long enough to sample the large inherent variability in the system on seasonal to inter-annual scales, most were deployed in the old Arctic climate system, and most were not interdisciplinary enough or of sufficient detail to characterize the complex, interdependent processes involved.
- Satellite-based retrievals and automated observing systems are a backbone of future Arctic observations, but these techniques are not yet adequately developed to provide the parameters and accuracy necessary for neither a process-level understanding nor for adequate monitoring and operational services. A long-term drifting observatory will be a platform from which the development of techniques and technology can occur.

Introducing MOSAiC

To develop the urgently needed understanding of central Arctic processes and improve their representation in models, it is proposed that a Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC) be established under international cooperation and leadership. The vision for MOSAiC, and the research program surrounding it, entails a balance of three primary activities: 1) A heavily instrumented, manned, drifting observatory accompanied by a research vessel (e.g., R/V Polarstern, R/V Amundsen) to be deployed in, and drift with, the sea-ice in the central Arctic Basin for 1-2 years; 2) A network of coordinated, disciplinary measurements to provide information on spatial variability, geographically-fixed processes, and/or large-scale context for the central observatory; and 3) A hierarchy of modeling activities ranging from high-resolution studies focused on process understanding and parameterization development to regional climate model simulations examining regional-scale processes and feedbacks and near-real time data assimilation into global numerical weather prediction models. A target deployment date for the primary MOSAiC observational campaign is autumn of 2018 in order to support planned international modeling activities in the central Arctic on that time frame. MOSAiC is also intentionally designed to cooperate with and integrate a variety of coordinated observational and modeling projects that target the central Arctic climate system. Scientific results and logistics experience from shorter-term field programs with more specialized objectives prior to MOSAiC, such as the Marginal Ice Zone Study (ONR-MIZ, Lee et al. 2012) in 2014 and the Arctic Ocean Drift Study (AODS, Polyakov et al. 2013) proposed for 2015, are valuable for the planning and implementation of MOSAiC. Detailed and developing information on MOSAiC is available at www.mosaicobservatory.org.

MOSAiC Scientific Goals and Objectives

The overarching goal of MOSAiC is to acquire the observations and perform model analyses needed to understand climate-relevant processes of the central Arctic Ocean climate system, cutting across many disciplines including atmosphere, sea-ice, ocean and biosphere. The dramatic transformation of the sea ice, to a new climate state dominated by first-year ice, will be an underlying theme and used as an integrator of change. With this concept in mind, an overarching science question that has been developed to guide MOSAiC is:

“What are the causes and consequences of an evolving and diminished sea ice cover?”

In support of this broad question, a number of sub-questions have also been developed in order to organize MOSAiC observational and modeling activities:

- How do ongoing changes in the Arctic ice-ocean-atmosphere system drive heat and mass transfers of importance to climate and ecosystems?
- What are the processes and feedbacks affecting sea ice cover, atmosphere-ocean stratification and energy budgets in the Arctic?
- Will an ice-reduced Arctic become more biologically productive and what are the consequences of this to other components of the system?
- How do the different scales of spatial and temporal heterogeneity within the atmosphere, ice and ocean interact to impact the linkages or feedbacks within the system?
- How do interfacial exchange rates, biology and chemistry couple to regulate the major elemental cycles?

There are several other important themes that cut across the MOSAiC objectives. To develop a detailed understanding of processes that affect the sea-ice, it is critical to study all aspects of the sea-ice life cycle. Ice growth and melt processes are directly related to energy fluxes, while sea-ice transport is related to momentum fluxes (wind forcing). As a drifting observatory, MOSAiC is intentionally designed to follow the ice in a Lagrangian framework, tracking the sea-ice as it integrates the various fluxes and changes. Importantly, the sea-ice is impacted by these fluxes in all seasons, and their balances determine the ultimate evolution and lifetime of sea-ice. Thus, it is imperative to observe critical processes that impact the sea-ice over the full annual cycle.

Additionally, while MOSAiC will last for 1-2 years, the need exists for improved capabilities for long-term, routine observations of key parameters over the sea-ice. The MOSAiC observatory will be an important test-bed for the development of automated observing systems and instruments for all disciplines, and for satellite observational techniques. It will also be a key component in a modeling test-bed for understanding the benefits of additional Arctic observations for global forecast skills.

MOSAiC Observational Activities

The central MOSAiC observational facility will be built around an ice-drift station with observations both on the ice and on a drifting platform. Observations on the ice are necessary for parameters sensitive to the immediate environment, while the platform is necessary as a base for heavy and expensive equipment, for power generation, for access to workshops and laboratory space, as a logistics center, and for safety reasons. This ice station will be the hub for intensive, inter-disciplinary observations to characterize detailed processes in the sea-ice, atmosphere, ocean, and ecosystem (Fig. 5).

For example, atmosphere observations will aim to characterize the vertical structure of atmospheric properties, including thermodynamic state, clouds, aerosols, turbulence, vertical mixing, precipitation, and radiation. Similarly, ocean measurements will target the vertical distribution of temperature, salinity, turbulent mixing, biological productivity, and elemental cycles. Importantly, all fluxes at both the top and bottom boundaries of the sea-ice will be measured, as well as internal sea-ice processes such as conduction, transmission, deformation, melt pond formation, and others. All observations will be designed with the complexity and accuracy needed to simultaneously characterize the myriad interdependent processes and feedbacks impacting the sea-ice (Fig. 6). The preferred platform for this comprehensive central observatory is an icebreaker (e.g., R/V Polarstern or R/V Amundsen), but a simpler vessel with capacity to survive but not necessarily to navigate in the ice may also be considered. The possibility to construct a on-ice runway for aircraft is also important.

In addition to the central, intensive, process-level observations, MOSAiC will utilize a constellation of coordinated observing platforms to gather information on the spatial heterogeneity and variability of processes on a variety of scales. To address this need, networks of distributed observations from the Russian “North Pole” drifting station, buoys, and remote, unmanned stations will be deployed over a large area surrounding the central observatory. The manned Russian drifting station will likely be a long-term observatory run in parallel with the international MOSAiC observatory to provide process-level observations at a second site in the Arctic Ocean, thereby collaborating scientifically and logistically. These networks will help to link the MOSAiC activity with existing, multi-year buoy-based observational programs, such as the French IAOOS Project (http://www.iaoos-equipex.upmc.fr/). Additionally, intensive, periodic, local-to-basin scale observations will be made using other research ships (e.g., R/V Mirai), research aircraft (e.g., Hoffmann et al. 2011; Herber et al. 2012), and unmanned vehicles in both the atmosphere and ocean to develop a clear understanding of spatial variability on scales ranging from the Arctic basin to model grid-boxes. Satellite observations will also be critical to provide a pan-Arctic perspective and provide linkages with intensive observational activities in other parts of the Arctic.

Fig. 5: Examples of the interdisciplinary measurements to be taken at the MOSAiC observatory (from Shupe et al 2012).

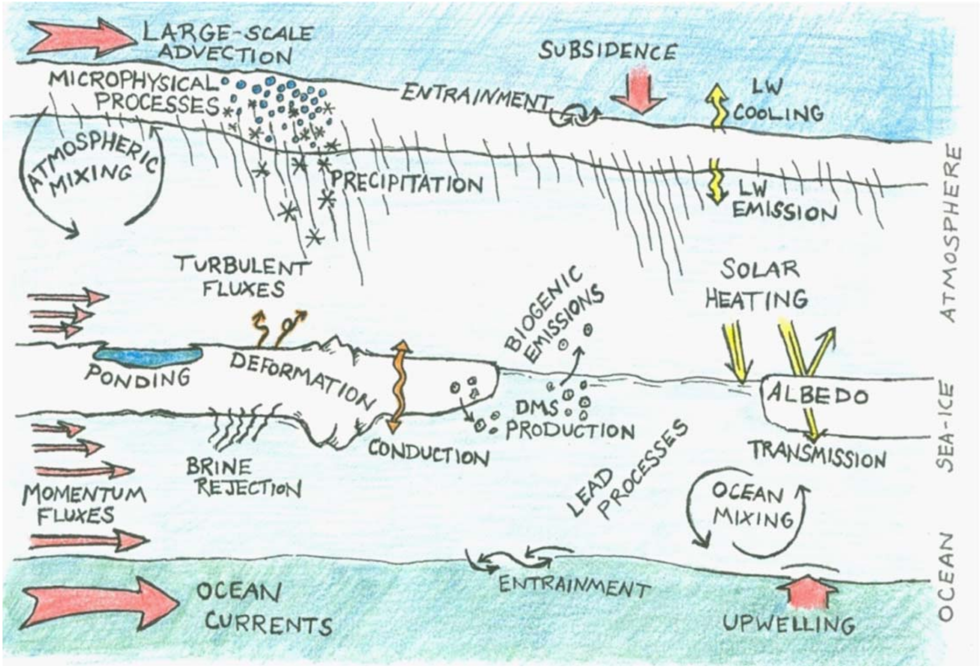


Fig. 6: Schematic showing some of the many interdisciplinary processes and process interactions to be the focus of MOSAiC (from Shupe et al 2012).

The exact drift track for the MOSAiC observatory needs to be considered in light of the continually evolving Arctic sea-ice pack. However, in order to capture the evolution of sea-ice through all seasons of the year and achieve the broader scientific goals and objectives, the best drift option is likely a transpolar drift (Fig. 1). Such a drift track would start in very young ice in the far Western Arctic Ocean (e.g., East Siberian Sea) and follow a trajectory through the central Arctic towards the Fram Strait over the course of 1-2 years. This observational phase of MOSAiC would ideally endure for many annual cycles, with potential re-deployment of resources as needed. Multiple annual cycles would allow for a better characterization of processes in all season and help capture more inter-annual variability. However, at an absolute minimum, a single, full annual cycle is required to observe the fundamental processes impacting the sea-ice in all seasons as it evolves.

Confronting Models with Observations during MOSAiC

MOSAiC is an important opportunity to gather the high quality and comprehensive observations needed to improve numerical modeling of critical, scale-dependent processes impacting Arctic predictability given diminished sea ice coverage and increased model complexity. Model improvements are needed to understand the effects of a changing Arctic on mid-latitude weather and climate. Additionally, better forecasting will be of high value for key economic areas, environmental planning, local populations, and governance in the Arctic, and can be used to quantify and assess the impact of a changing Arctic on natural resource development, transportation, fisheries, ecosystems, and tourism. Lastly, model studies are a critical means for integrating detailed observations towards broader, system-level understanding.

The basic premise of MOSAiC is that model improvements can best be realized through enhanced, process-level model parameterizations. Specific needs identified by the modeling community have been integral in the design of MOSAiC from the beginning. Thus, MOSAiC is specifically designed to provide the multi-parameter, coordinated observations needed to improve parameterizations. For example, the observational campaign will capture processes as they manifest in all seasons of the year, rather than only in short, season-specific periods. Over the annual cycle, the spatial heterogeneity of key processes and parameters will be characterized to help ensure that parameterizations are sufficiently flexible and broadly representative.

To facilitate, evaluate, and develop the needed model improvements, MOSAiC will employ a hierarchy of modeling approaches ranging from process model studies, to regional and global climate model intercomparisons, to operational forecasts and assimilation of real-time observations. Model evaluations prior to the field program will be used to identify specific gaps and parameterization needs. Preliminary modeling and operational forecasting will also be necessary to directly guide field planning and optimal implementation of field resources, and to support the safety of the project.

As an example of planned model activities, detailed, local-scale processes will be studied within the context of the mesoscale environment using nested Weather Research and Forecasting (WRF) model simulations with high-resolution inner nested domains that are equivalent to large eddy simulation (LES) models (e.g., Solomon et al. 2009, 2011). The outer domains of this type of model are appropriate for comparisons with spatially-distributed MOSAiC measurements, which will provide guidance and constraints on the mesoscale environment. Inner model domains will be more comparable to the complex and detailed observations made at the central MOSAiC observatory. Such observations will provide robust constraints on model processes, while the model will provide insight into detailed exchange processes and budgets that cannot be observed (e.g., Solomon et al. 2011). These nested process models importantly provide a means for upscaling detailed process representations to models with coarser resolution.

At the Regional Climate Model (RCM) scale, an intercomparison will be conducted similar to the Arctic Regional Climate Model Intercomparison Project (ARCMIP) based on SHEBA observations (Tjernström et al. 2005; Rinke et al. 2006; Wyser et al. 2008). The objective of this intercomparison will be to assess and document the performance of numerous international atmospheric RCMs over the Arctic Ocean utilizing the detailed MOSAiC measurements and any other data available from contemporary campaigns or operational stations. Numerical Weather Prediction (NWP) models will also be included, such as the

European Hirlam and Harmonie, and the American WRF models. Simulations will be conducted over a full annual cycle for atmosphere-only models run in forecast and climate mode configurations. The roles of clouds, aerosols, planetary boundary layer processes, precipitation, atmospheric vertical structure, Arctic baroclinic cyclones, and vertical exchanges of heat, moisture, and momentum will be evaluated with the appropriate measurements.

Process deficiencies found in recent (e.g., Proshutinsky et al. 2012; Popova et al. 2012) and near-future regional ocean modeling intercomparison studies will also be used to guide the observations during MOSAiC. Topics defined by these studies include the circulation pathways of the Atlantic and Pacific waters; impacts of wind and atmospheric thermal forcing; freshwater dynamics and life-cycle; vertical ocean mixing; and ecosystem primary productivity. The MOSAiC observations will also be used for future ocean, sea-ice and biological process modeling, similar to that described for the atmosphere. Hopefully, the MOSAiC observations and process studies will allow future Regional Climate Model Intercomparisons for the Arctic Ocean that include truly coupled models where complex feedbacks between atmosphere, sea-ice and ocean are interactively simulated, as in Dorn et al. (2012). Uncertainties in the prescribed atmospheric forcing may have produced many of the problems in the modeled sea-ice thickness distributions and impacted the ocean circulation in the above studies (Proshutinsky et al. 2012).

MOSAiC modeling activities will be an area of active collaboration with the WCRP and WWRP Polar Prediction Initiative projects. The aim of the WCRP initiative is to understand the drivers of Arctic sea ice loss and to better predict the rate of ice loss with the help of improved NWPs and GCMs. One key element of this initiative will be the Year of Polar Prediction (YOPP) that is planned for approximately the 2018 time frame. MOSAiC will be specifically coordinated with the YOPP with the intention of MOSAiC observations serving as a testbed for a variety of international YOPP-related modeling activities.

Next Steps for MOSAiC

Continued coordination through IASC will ascertain that MOSAiC remains a truly international endeavor; while broad coordination has already occurred between European and North American contingencies, a special emphasis is being placed on engaging the Russian and Asian research communities as well. A project of this scope will simply not be possible without full international collaboration. The international framework is necessary from a resource and funding perspective and also for access, permissions and logistics considerations. IASC will monitor the development of science and implementation plans and decide on the international leadership of the effort as it leaves the drawing board and moves towards implementation.

Furthermore, the Arctic Ocean is a region whose changes impact not only the Arctic nations but the entire globe. Funding must come from multiple sources, from agencies in different countries and regions; a special challenge will be to coordinate the funding across national or regional borders. Many different projects will come to fall under the MOSAiC umbrella such as, for example, the ECRA initiative in the European Union.

During the first half of 2013 an interdisciplinary science plan will be developed, based on the outcome of prior planning workshops. A cross-cutting theme within the IASC framework is being developed in 2013, and coordination with AOS and SAON will be pursued the first half of 2013 and beyond. This will lay a foundation for discussions and coordination with international funding agencies and logistics coordinators. A MOSAiC Open Science meeting will be planned for 2014 to draw broader participation.

References

Asplin, M. G., R. Galley, D. G. Barber, and S. Prinsenberg, 2012: Fracture of summer perennial sea ice by ocean swell as a result of arctic storms. *J. Geophys. Res. C. Oceans*, **117** (C6).

Bottenheim, J. W., Netcheva, S., Morin, S., & Nghiem, S. V. (2009). Ozone in the boundary layer air over the arctic ocean: Measurements during the TARA transpolar drift 2006-2008. *Atmospheric Chemistry and Physics, 9*(14), 4545-4557. Retrieved from http://search.proquest.com/docview/809155289?accountid=28266

Curry, J. A., D. Randall, W. B. Rossow, and J. L. Schramm, Overview of Arctic cloud and radiation characteristics, *J. Climate*, **9**, 1731-1764, 1996.

Dorn, W., K. Dethloff, and A. Rinke, 2012: Limitations of a coupled regional climate model in the reproduction of the observed Arctic sea-ice retreat, *The Cryosphere*, **6**, 985-998, doi:10.5194/tc-6-985-2012.

Francis, J. A., and S. J. Vavrus, 2012: Evidence linking Arctic amplification to extreme weather in mid-latitudes. *Geophys. Res. Lett*., **39**, L06801, doi:10.1029/2012GL051000.

Francis, J. A., W. Chan, D. J. Leathers, J. R. Miller, and D. E. Veron, 2009a: Winter Northern Hemisphere weather patterns remember summer Arctic sea-ice extent, *Geophys. Res. Lett*., **36**, L07503, doi:10.1029/2009GL037274

Francis, J. A., D. M. White, J. J. Cassano, W. J. Gutowski Jr, L. D. Hinzman, M. M. Holland, M. A. Steele, and C. J. Vörösmarty, 2009b: An arctic hydrologic system in transition: Feedbacks and impacts on terrestrial, marine, and human life. *J. Geophys. Res. G. Biogeosciences,* **114**, G04019, doi:10.1029/2008JG000902

Graversen, R. G., 2006: Do changes in the midlatitude circulation have any impact on the Arctic surface air temperature trend? *J. Clim*., **10**, 5422-5438.

Graversen, R. G., T. Mauritsen, M. Tjernström, E. Kallén, and G. Svensson, 2009: Vertical structure of recent Arctic warming. *Nature* 451, 53-56 (3 January 2008) | doi:10.1038/nature06502

Herber, A. , C. Haas, R. S. Stone, J. W. Bottenheim, L. Peter , S. M. Li, R. Staebler, J. W. Strapp, and K. Dethloff, 2012: Regular airborne surveys of Arctic sea ice and atmosphere , EOS, Transactions, Amer. Geophys. Union, **93** (4), pp. 41-42 . hdl:10013/epic.38685

Hoffmann, A., Osterloh, L., Stone, R., Lampert, A., Ritter, C., Stock, M., Tuneved, P., Hennig, T., Böckmann, C., Li, S. M., Eleftheriadis, K., Maturilli, M., Orgis, T., Herber, A., Neuber, R. and Dethloff, K., Remote sensing and in-situ measurements of tropospheric aerosol, a PAMARCMiP case study, *Atmos. Env.*, **52**, 56-66, doi:10.1016/j.atmosenv.2011.11.027, 2011.

Inoue, J., and M. E. Hori 2011: Arctic cyclogenesis at the marginal ice zone: A contributory mechanism for the temperature amplification? *Geophys. Res. Lett*., **38**, L12502, doi:10.1029/2011GL047696.

Inoue, J., M. E. Hori, T. Enomoto, and T. Kikuchi, 2009: Intercomparison of surface heat transfer near the marginal ice zone for multiple reanalyses: A case study of September 2009. *SOLA*, **7**, 57-60, doi:10.2151/sola.2011-015.

Intrieri, J.M., C.F. Fairall, M.D. Shupe, P.O.G. Persson, E.L Andreas, P. Guest, and R.M. Moritz, 2002: Annual cycle of cloud forcing over the Arctic. *J. Geophys. Res*., **107** (C10), 10.1029/2000JC000439.

Jaiser, R., Dethloff, K., Handorf, D., Rinke, A. and Cohen, J., Impact of sea ice cover changes on the Northern Hemisphere atmospheric winter circulation, *Tellus A 2012*, **64**, 11595, doi:10.3402/tellusa.v64i0.11595, 2012.

Kay, J. E., T. L'Ecuyer, A. Gettelman, G. Stephens, and C. O'Dell, 2008: The contribution of cloud and radiation anomalies to the 2007 Arctic sea ice minimum. *Geophys. Res. Lett.*, **35**, L08503, doi:10.1029/2008GL033451.

Klaus, D., Dorn, W., Dethloff, K., Rinke, A. and Mielke, M., Evaluation of two cloud parameterizations and their possible adaptation to Arctic climate conditions, *Atmosphere*, **3 (3)**, 419-450, doi:10.3390/atmos3030419, 2012.

Kwok, R., and N. Untersteiner, 2011: The thinning of Arctic sea ice, *Physics Today*, April 2011, 36-41.

Lampert, A., Maturilli, M., Ritter, C., Hoffmann, A., Stock, M., Herber, A., Birnbaum, G., Neuber, R., Dethloff, K., Orgis, T., Stone, R. S., Brauner, R., Kässbohrer, J., Haas, C., Makshtas, A., Sokolov, V. and Liu, P., The spring-time boundary layer in the central Arctic observed during PAMARCMiP 2009, *Atmosphere*, **3 (3)**, 320-351, doi:10.3390/atmos3030320, 2012.

Leck, C., and E. K. Bigg, 2007: A modified aerosol-cloud-climate feedback hypothesis. *Environ. Chem*., **4**, 400-403.

Lee, C. M., and 20 others, 2012: Marginal Ice Zone (MIZ) Program: Science and Experiment Plan. Technical Report APL-UW 1201, October 2012. [Available from http://www.apl.washington.edu/research/downloads/publications/tr_1201.pdf]

Lindsay, R. W., Temporal variability of the energy balance of thick Arctic pack ice, *J. Clim.*, **11**, 313-333, 1998.

Long, Z., and W. Perrie, 2012: Air-sea interaction during an Arctic storm. *J. Geophys. Res*., **117** D15103, doi:10.1029/2011JD016985.

Maykut, G. A., Large-scale heat exchange and ice production in the Central Arctic, *J. Geophys. Res*, **87**, C10, 7971-7984, 1982.

Mohn, H., *The Norwegian North Polar Expedition 1893-1896, Scientific Results*, Volume VI, Meteorology, edited by F. Nansen, F. Nansen Fund for Advancement of Science, Christiania (Oslo), 1905.

Morison, J., K. Aagaard, K. Falkner, T. Kikuchi, M. McPhee, D. Moritz, J. Overland, T. Stanton, and M. Steele, 2006: The North Pole Environmental Observatory: A community resource tracking a changing Arctic through the International Polar Year. *EOS*, *Trans. Am. Geophys. Union*, **87** (36), suppl., Sep. 2006.

Orellana, M. V., P. A. Matrai, C. Leck, C. D. Rauschenberg, A. M. Lee, and E. Coz, 2011: Marine microgels as a source of cloud condensation nuclei in the high Arctic. *PNAS*, Aug 16, **108** (33) 13612-13617.

Overland, J. E., and M. Wang, 2010: Large-scale atmospheric circulation changes associated with the recent loss of Arctic sea ice. Tellus **62A**: 1–9.

Perovich, D., K., E.L., Andreas, J.A. Curry, H. Eiken, C.W. Fairall, T.C. Grenfell, P.S. Guest, J.M. Intrieri, D. Kadko, R.W. Lindsay, M.G. McPhee, J. Morison, R.E. Moritz, C.A. Paulson, W.S. Pegau, P.O.G. Persson, R. Pinkel, J.A. Richter-Menge, T. Stanton, H. Stern, M. Sturm, W.B. Tucker III, and T. Uttal, 1999: Year on ice gives climate insights. *Eos, Trans., AGU, 80* [41], 481-486.

Perovich, D. K., J. A. Richter-Menge, K. F. Jones, and B. Light, 2008: Sunlight, water, and ice: Extreme Arctic sea ice melt during the summer of 2007. *Geophys. Res. Lett.*, **35**, L11501, doi:10.1029/2008GL034007.

Persson, P. O. G., 2012: Onset and end of the summer melt season over sea ice: Thermal structure and surface energy perspective from SHEBA. *Clim. Dynamics*, **39**, 1349-1371, DOI: 10.1007/s00382-011-1196-9.

Persson, P. Ola G., C. W. Fairall, E. L. Andreas, P. S. Guest, and D. K. Perovich, 2002: Measurements near the Atmospheric Surface Flux Group tower at SHEBA: Near-surface conditions and surface energy budget. *J. Geophys. Res.* **107**(C10), 8045, doi:10.1029/2000JC000705.

Persson, P. O. G., T. Uttal, J. M. Intrieri, C. W. Fairall, E. L. Andreas, and P. S. Guest, 1999: Observations of large thermal transitions during the Arctic night from a suite of sensors at SHEBA. *Preprints, 3rd Symp. on Integrated Observing Systems*., Jan. 10-15, 1999, Dallas, TX, 171-174.

Polyakov, I. V., et al., 2010: Arctic Ocean warming reduces polar ice cap, *J. Phys. Oceanogr.*, DOI: 10.1175/2010JPO4339.1, **40**, 2743–2756.

Polyakov, I. V., *et al*., 2011: Fate of early-2000's Arctic warm water pulse, *Bulletin of American Meteorological Society*. May 2011, 1–6, DOI:10.1175/2010BAMS2921.1.

Polyakov, I., and 35 others, 2012: Surface heat and freshwater budgets in the eastern Eurasian Basin: Ship-supported ice-camp measurements of atmospheric and oceanic forcing contributing to Arctic sea ice loss. White paper, available at http://arcticchange.squarespace.com/aods-documents/

Popova, E. E., A. Yool, A. C. Coward, F. Dupont, C. Deal, S. Elliott, E. Hunke, M. Jin, M. Steele, and J. Zhang, 2012: What controls primary production in the Arctic Ocean? Results from an intercomparison of five general circulation models with biogeochemistry, *J. Geophys. Res*., **117**, C00D12, doi:10.1029/2011JC007112

Proshutinsky, A., Y. Aksenov, J. Clement Kinney, R. Gerdes, E. Golubeva, D. Holland, G. Holloway, A. Jahn, M. Johnson, E. Popova, M. Steele, and E. Watanabe. 2011. Recent advances in Arctic ocean studies employing models from the Arctic Ocean Model Intercomparison Project. *Oceanography* **24**(3):102–113, http://dx.doi.org/10.5670/oceanog.2011.61.

Proshutinsky, A., J. Yang, R. Krishfield, R. Gerdes, M. Karcher, F. Kauker, C. Koeberle, S. Hakkinen, W. Hibler, D. Holland, and others. 2005. Arctic Ocean study: Synthesis of model results and observations. *Eos, Transactions, American Geophysical Union* **86**(40):368, http://dx.doi.org/10.1029/2005EO400003

Rinke, A. , K. Dethloff, J. Cassano, J. H. Christensen, J. A. Curry, J. E. Haugen, D. Jacob, C. Jones, M. Koltzow, A. H. Lynch, S. Pfeifer, M. C. Serreze, M. J. Shaw, M. Tjernström, K. Wyser, and M. Zagar, 2006: Evaluation of an ensemble of Arctic regional climate models: Spatiotemporal fields during the SHEBA year , Climate Dynamics, **26** , 459-472, doi:10.1007/s00382-005-0095-3 , hdl:10013/epic.20786

Rinke, A. and K. Dethloff, 2008: Simulated circum-Arctic climate changes by the end of the 21st century , Global and Planetary Change, 62, 173-186, doi: 10.1016/j.gloplacha.2008.01.004. hdl:10013/epic.30447

Shimada, K., T. Kamoshida, M. Itoh, S. Nishino, E. Carmack, F. McLaughlin, S. Zimmermann, and A. Proshutinsky, 2006: Pacific Ocean inflow: Influence on catastrophic reduction of sea ice cover in the Arctic Ocean, *Geophys. Res. Lett.*, **33**, L08605, doi:10.1029/2005GL025624.

Shupe, M.D. and J.M. Intrieri, 2004: Cloud radiative forcing of the Arctic surface: The influence of cloud properties, surface albedo, and solar zenith angle. *J. Climate*, **17**, 616-628.

Shupe, M., O. Persson, M. Tjernström, and K. Dethloff, 2012: MOSAiC: Multidisciplinary drifting Observatory for the Study of Arctic Climate. Abstract C44A-05 presented at 2012 Fall Meeting, San Francisco, Calif., USA, 3-7 Dec.

Solomon, A, H Morrison, O Persson, M Shupe, and J-W Bao, 2009: Investigation of microphysical parameterizations of snow and ice in Arctic clouds during M-PACE through model-observation comparisons. *Mon. Wea. Rev.*, **137**, 3110-3128

Solomon, A., M. D. Shupe, P. O. G. Persson, and H. Morrison, 2011: Moisture and dynamical interactions maintaining decoupled Arctic mixed-phase stratocumulus in the presence of a humidity inversion. Atmos. Chem. Phys., 11, 10 127 – 10 148.

Solomon, S. *et al.* (eds) Climate Change 2007: The Physical Science Basis (Cambridge Univ. Press, Cambridge, UK, 2007)

Steele, M., J. Zhang, and W. Ermold, 2010: Mechanisms of summertime upper Arctic Ocean warming and the effects on sea ice melt. *J. Geophys. Res.*, **115**, C11004, doi:10.1029/2009JC005849.

Stramler, K., A. D. Del Genio, and W. B. Rossow, 2011: Synoptically driven Arctic winter states. *J. Clim.,* **24** (6), 1747-1762.

Tjernström, M., J. Sedlar, and M. D. Shupe, 2008: How well do regional climate models reproduce radiation and clouds in the Arctic? An evaluation of ARCMIP simulations. *J. Appl. Meteorol. Clim.*, **47**:2405. doi:10.1175/2008JAMC1845.1

Vihma, T., J. Jaagus, E. Jakobson, and T. Palo, 2008: Meteorological conditions in the arctic ocean in spring and summer 2007 as recorded on the drifting ice station tara. *Geophysical Research Letters, 35*(18) doi: http://dx.doi.org/10.1029/2008GL034681

Walsh, J. E., W. L. Chapman and D. H. Portis, 2009: Arctic cloud fraction and radiative fluxes in atmospheric reanalyses. *J. Climate*, **22**, pp. 2316-2334, doi: 10.1175/2008JCLI2213.1

Wang, X. and J. R. Key, 2005: Arctic surface, cloud, and radiation properties on the AVHRR polar pathfinder dataset. Part II: Recent trends. *J. Climate*, **18**, 2575–2593.

Wyser, K. , C. G. Jones, P. Du, E. Girard, U. Willén, J. Cassano, J. H. Christensen, J. A. Curry, K. Dethloff, J.E. Haugen, D. Jacob, M. Koltzow, R. Laprise, A. Lynch, S. Pfeifer, A. Rinke, M. Serreze, M. J. Shaw, M. Tjernström, and M. Zagar, 2008: An evaluation of Arctic cloud and radiation processes during the SHEBA year: simulation results from eight Arctic regional climate models., *Clim. Dyn.*, **30**, pp. 203-223. doi:10.1007/S00382-007-0286-1 , hdl:10013/epic.28150