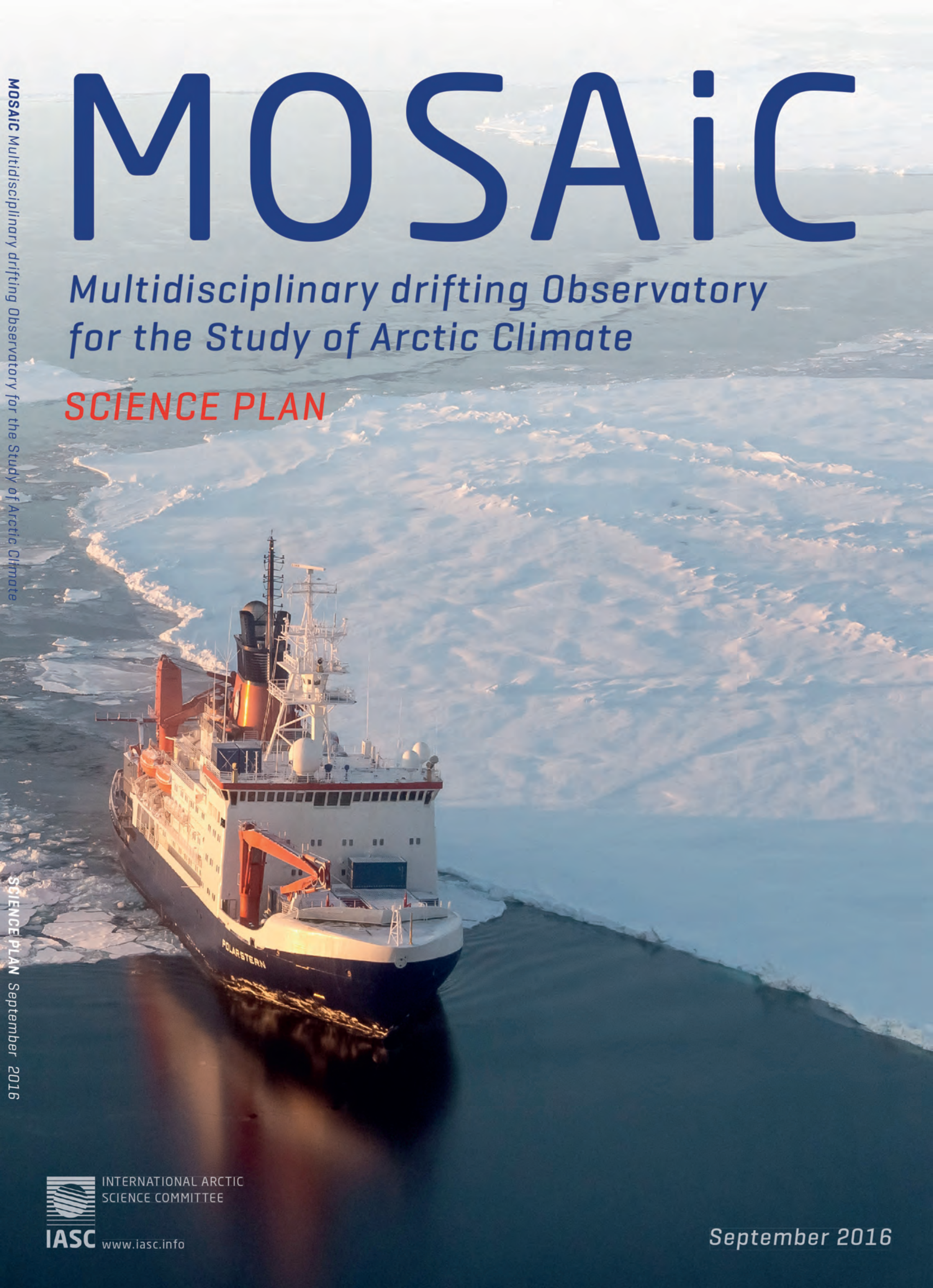

# MOSAiC

## Multidisciplinary drifting Observatory for the Study of Arctic Climate

## SCIENCE PLAN

**MOSAiC** Multidisciplinary drifting Observatory for the Study of Arctic Climate

**SCIENCE PLAN** September 2016

INTERNATIONAL ARCTIC
SCIENCE COMMITTEE
IASC www.iasc.info

September 2016

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## *Multidisciplinary drifting Observatory*
## *for the Study of Arctic Climate*

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*September 2016*

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## EXECUTIVE SUMMARY

The ***M**ultidisciplinary drifting **O**bservatory for the **S**tudy of **A**rct**i**c **C**limate* (MOSAiC) is an international Arctic research initiative that is broadly motivated by the dramatic changes in the Arctic climate system over the last few decades, highlighted by significant losses of sea ice, and generally deficient model representations of the important processes responsible for, and responding to, these changes. The ultimate goal of the initiative is to enhance understanding of central Arctic coupled atmosphere-ice-ocean-ecosystem processes to improve numerical models for sea ice forecasting, extended-range weather forecasting, climate projections, and climate change assessment.

### *Science Design*

At the top level, MOSAiC is organized around the broad science question: *What are the causes and consequences of an evolving and diminished Arctic sea ice cover*? Sea ice acts as the central organizational element for MOSAiC; it is an integrator of change in the Arctic climate system as it responds to variations in fluxes and forcings that occur via thermodynamics, dynamics, and other processes. Moreover, the sea ice serves as an important interface in a complex coupled Arctic system where it modulates the flow of energy, moisture, particles, and gases, and serves as a substrate for biological activity. Coordinated with the top-level science question is a suite of related sub-questions around which the specific observational and modeling activities of MOSAiC are organized:

1) What are the seasonally-varying energy sources, mixing processes, and interfacial fluxes that affect the heat and momentum budgets of the Arctic atmosphere, ocean and sea ice?

2) How does sea ice formation, drift, deformation and melting couple to atmospheric, oceanic and ecosystem processes?

3) What are the processes that regulate the formation, properties, precipitation and life time of Arctic clouds and their interactions with aerosols, boundary layer structure and atmospheric fluxes?

4) How do interfacial exchange rates of biogeochemical process- related trace gases trigger the Arctic climate system?

5) How do sea ice and pelagic ecosystems respond to changes in Arctic sea ice?

6) How do ongoing changes in the Arctic climate system impact large-scale heat, momentum and mass fluxes and how do these changes feed back into the Arctic climate and ecosystem?

MOSAiC is a comprehensive, interdisciplinary and sustained process study. Each organizational science question explores important processes participating in a highly coupled system, and each is guided by significant deficits in process-level understanding and model representation. One tenant of MOSAiC is that these interdependent processes must be examined simultaneously because of the importance of coupling, feedbacks, and seasonality in the system. *The scope of observing activities is thus based on those aspects of the Central Arctic climate system that participate in climate-relevant feedbacks and interactions with other elements of the system.* A singular focus on any individual element of the system will fail to provide the comprehensive, process-level understanding that is needed. *Continuity* and *seasonality* are also extremely important concepts. Coupled system processes in the sea ice environment evolve over the course of the year in response to seasonal cycles and episodic events. To understand any state of the system requires understanding prior states and how these evolve on seasonal scales. Thus, it is essential that observing activities are conducted for at least a full annual cycle. Finally, the Arctic system is *heterogeneous* on many temporal and spatial scales. Thus, MOSAiC is designed to characterize heterogeneity on the appropriate scales to support model representations of this variability.

### *Science Implementation*

To address the MOSAiC science objectives, the initiative will involve a combination of observing, modeling, and synthesis activities. Field observations will follow a multi-tiered approach that includes: 1) A Central Observatory for characterizing detailed coupled-system processes in the atmosphere, sea ice, ocean, and ecosystem; 2) A distributed regional network around the Central Observatory comprised of autonomous and remotely-operated sensor systems for characterizing spatial variability and heterogeneity of key processes; and 3) Coordination with other observational activities across the Arctic Basin domain for linkages with pan-Arctic processes. The observations made at each of these scales will provide important context and detail for those made at other scales. Most of the associated measurements will be conducted operationally for the duration of the MOSAiC field phase, while there will also be episodic intensive observing periods that focus on individual processes or seasonally-specific aspects of the system. The Central Observatory and distributed regional network will drift with the sea ice over the full annual cycle. This sea ice Lagrangian approach offers the ability to observe the sea ice life cycle, extending from freezing through growth, deformation, and transport, towards melt, decay, and export. Along this path, observations will be designed to characterize exchange processes in the system, and measure physical, chemical and biological interactions across the atmosphere-ice-ocean system.

These comprehensive field measurements over an annual cycle in the Central Arctic will facilitate wide-reaching modeling, synthesis, and integration activities to support improved process-level model representations and lead to enhanced model forecasting abilities. Hierarchical, multi-scale model activities will help bridge across the range of spatial and temporal scales necessary to link the focused observations with regional and global processes of importance. High-resolution and process models will be used to interface with the detailed observations made across the MOSAiC constellation and to complement these observations towards developing process understanding. Single column models will be used to test and evaluate model parameterizations that are used in larger-scale models. Increased operational measurements of some parameters will allow for detailed assessment of model assimilation systems and the influence of additional data on forecasting abilities. Regional models, both coupled and uncoupled, will offer the ability to upscale the detailed observing and process-modeling information to pan-Arctic scales and to facilitate coupled-system integration. All of these activities will ultimately lead to improved coupled-system representation in large-scale models that are used to forecast weather, predict climate, and study global scale interactions.

### *Towards the Future*

This Science Plan lays out the scientific vision and context for MOSAiC. To successfully implement this interactive, inter-disciplinary and coupled-system science plan will require strong leadership and coordination of international and interagency science, infrastructure, and funding contributions. This process requires a well-designed Implementation Plan that outlines observational requirements, deployment, the drift path, logistical plans, allocation of field personnel, operational modeling and forecasting, safety protocols, and education and outreach activities. The plan must also outline a strong data management plan that will preserve the MOSAiC legacy and facilitate its use by research and stakeholder communities.

# 1. INTRODUCTION

The ***M****ultidisciplinary drifting* ***O****bservatory for the* ***S****tudy of* ***A****rcti****c*** ***C****limate* (MOSAiC) is an international Arctic research initiative that is broadly motivated by the dramatic changes in the Arctic climate system over the last few decades, highlighted by significant losses of sea ice, and generally deficient model representations of the important processes responsible for, and responding to, these changes. The ultimate goal of the initiative is to enhance process-level understanding of the coupled central Arctic climate system that will improve numerical models for sea ice forecasting, extended-range weather forecasting, climate projections, and climate change assessment. The objectives of this "Science Plan" document are to lay out the overarching motivations for the initiative, convey the specific science objectives and questions around which the program is organized, and outline detailed observational and modeling plans for addressing these objectives. Plans contained herein will serve as a guide for interested scientific investigators, a means for linking MOSAiC with collaborating Arctic research programs, and a roadmap for coordinating international funding agency contributions to the broader effort. It is anticipated that this plan will be enhanced, updated, and adapted in response to specific agency contributions and as logistical implementation details are established.

The conceptual design of MOSAiC includes three basic components: 1) An intensive Central Observatory embedded within the primarily first year sea ice of the central Arctic supporting comprehensive measurements in the atmosphere, sea ice, ocean, and ecosystem; 2) a constellation of distributed measurements from manned, unmanned, and autonomous platforms to characterize spatial variability and heterogeneity on model grid-box scales; and 3) a hierarchy of analysis and modeling activities, on a variety of scales from individual processes to regional and global modeling, to consolidate and integrate information from the observational testbed. MOSAiC will be coordinated with a variety of pan-Arctic observing, analysis, and modeling activities, many associated with the WMO-sponsored Year of Polar Prediction (YOPP). Each of these elements will be described in detail in this document.

The MOSAiC initiative has been organized under the auspices of the International Arctic Science Committee (IASC), with support and guidance from its Atmosphere, Cryosphere, and Marine working groups. Additional support has come from a number of other institutions including the Alfred Wegener Institute, University of Colorado/NOAA-ESRL-PSD, WWRP Polar Prediction Project, WCRP Climate and Cryosphere (CliC) committee, and many others. Being international in nature, MOSAiC is targeting significant coordinated support from a broad range of funding agencies within Europe, North America, and Asia. Additionally, the intention is for MOSAiC to complement and coordinate with existing Arctic research programs that are already established in the E.U., U.S., Canada, Russia, China, Japan, Korea, and others.

This Science Plan document is organized as follows: Section 1 provides scientific motivation for MOSAiC, insight into the historical context for the project, and a more detailed introduction of the programmatic strategy. Section 2 outlines the specific science objectives, questions, and themes that serve to organize the MOSAiC endeavor. Experimental plans for making the necessary measurements are expanded upon in Section 3. Section 4 includes plans for synthesis activities, including modeling at multiple scales. Section 5 offers a short statement on implementation considerations and concludes with a list of contributors and contributions to this plan.

## 1.1. Scientific Motivation

The Earth's climate system is changing as a result of increased greenhouse gas concentrations and their associated net warming effects. Warming is particularly pronounced in the Arctic, where regional temperatures are rising at more than twice the rate as the rest of the globe (Hansen et al. 2010). This so-called Arctic Amplification effect has been largely attributed to significant regional feedback processes associated with a changing cryosphere (e.g., Serreze & Barry 2011; Screen & Simmonds 2010; Comiso & Hall 2015), and makes the Arctic an ideal laboratory for studying the manifestation of global change.

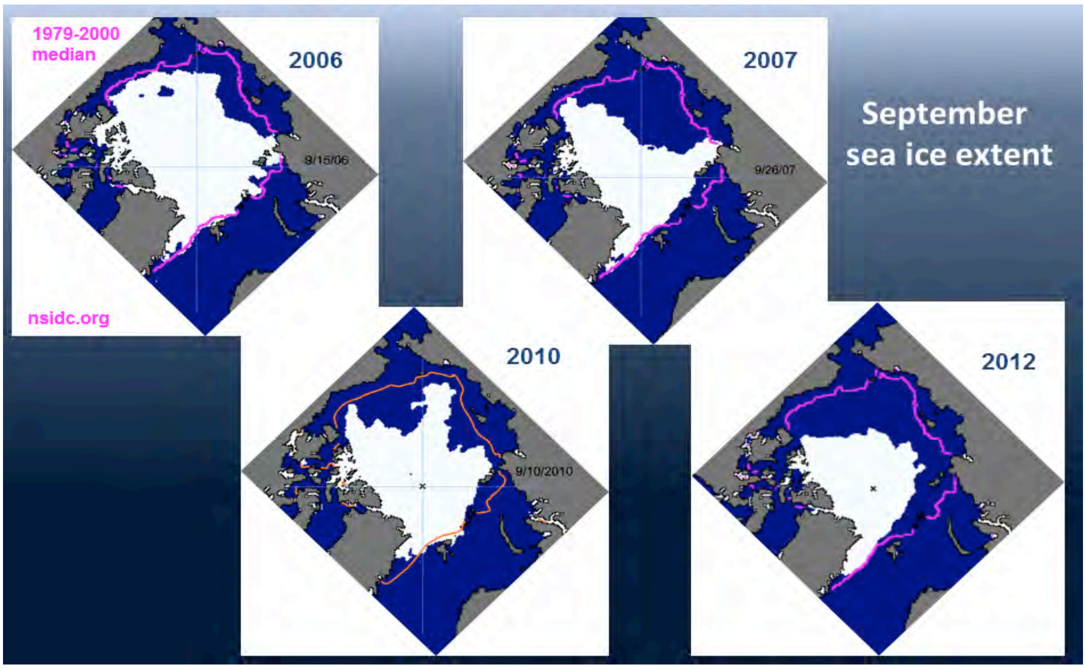


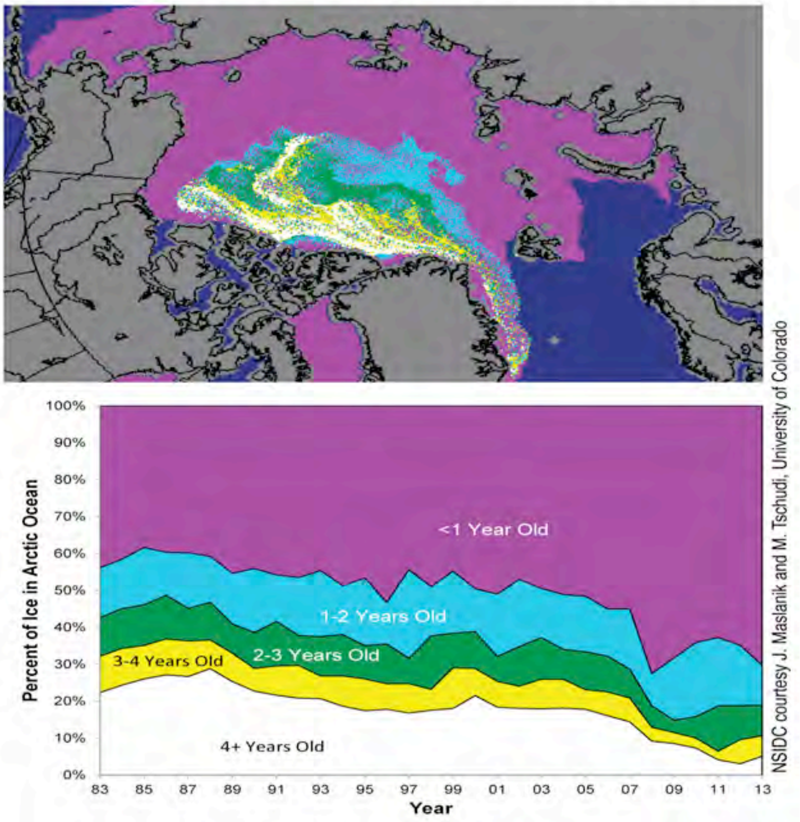
**Fig. 1.1:** September minimum sea ice extent for four different years, compared to the 1979-2000 median. Images courtesy of the National Snow and Ice Data Center (nsidc.org).

One of the first and most visible signs of global and Arctic regional change is the dramatic decline in sea ice observed over the past few decades (Comiso 2002; Stroeve et al. 2007; Simmonds 2015). September annual minimum sea ice extent reached record minima in 2005, 2007, and 2012, with 2012 showing a 49% decrease relative to the 1979-2000 median (Overland & Wang 2013; Figure 1.1). In addition to being less spatially extensive, the ice pack is also becoming younger and thinner (Kwok & Rothrock 2009; Maslanik et al. 2011; Lindsay & Schweiger 2015), moving from an ice pack dominated by multi-year ice to one consisting primarily of first-year ice (Figure 1.2). These changes invoke many important marine-based feedback processes related to the reflectivity of the surface, the productivity of ocean waters, and others (e.g., Meier et al. 2014). Additionally, associated changes and feedbacks on the terrestrial side related to processes such as methane release from permafrost melt and changing ice sheet mass balances promise to further enhance and amplify Arctic changes (e.g., Koven et al. 2011). Clearly a “new” Arctic is emerging, with observed changes that are significant relative to the observational record (e.g., Meier et al. 2007).

Implications of the Arctic in transition, and particularly the changing state of Arctic sea ice and ocean conditions, are becoming increasingly apparent and important. Expanding seasonally ice-free oceans offer new opportunities for resource development, shipping, and other commercial interests (Meier et al. 2014). The summer of 2013 saw the first container-transporting cargo ship transect the Arctic, trimming two weeks off the typical transit time from China to Europe. Additionally, major movements towards seasonally, operational off-shore oil drilling have occurred in Russian and U.S. waters in 2012 and 2013. As these lucrative activities draw more commercial development to the Arctic, it becomes increasingly important to understand and forecast sea ice in the region.

Arctic ecosystems and communities that are uniquely adapted to extreme conditions are also affected by change. While the shrinking habitat for polar bears is one of the most widely panned changes (Durner et al. 2009), there are numerous implications further down the food chain (e.g., Huntington 2009; Grebmeier et al. 2010; Kovacs et al. 2011) that impact ecosystem stability, biodiversity, nutrient cycles, fisheries, and more. Diminished sea ice contributes to a warmer, fresher, and more acidic upper Arctic Ocean, which has implications on the biological pump

(Lalande et al. 2011). Sea ice declines have also been linked to increases in Arctic Ocean primary production (Arrigo et al. 2008; Fernandez-Mendez et al. 2015). These changes and others have profound sociocultural impacts on northern communities via subsistence practices, regional transportation, and community identity (e.g., Lovecraft 2013).



NSIDC courtesy J. Maslanik and M. Tschudi, University of Colorado

**Fig. 1.2:** Arctic sea ice age in March 2013 (upper), and the spatial distribution of sea ice as a function of age over the past 30 years (lower). Images courtesy of the US National Snow and Ice Data Center, Jim Maslanik and Mark Tschudi.

Repercussions of Arctic change may extend beyond the Arctic itself, potentially impacting northern hemisphere synoptic circulation patterns, global teleconnections, and lower-latitude weather. Studies suggest that more spatially-extensive open ocean modifies the ocean heat storage and release, impacting atmospheric thickness and large-scale circulation patterns (Overland & Wang 2010). Associated weakened zonal flow and increased large-scale wave amplitudes are hypothesized to generate slower propagating Rossby waves increasing the likelihood of extreme weather events at mid-latitudes (Francis & Vavrus 2012; Petoukov et al. 2013; Tang et al. 2014). Some have suggested that these links may not be statistically or physically robust (Barnes 2013; Screen et al. 2014), and may be driven by lower latitude variability (Screen et al. 2012; Peings & Magnusdottir 2014). Notwithstanding this important debate about large-scale linkages, changes in sea ice and ocean heat fluxes have been implicated in amplifying the Siberian high leading to cold conditions in far East Asia (Honda et al. 2009), cold winters in Europe (Yang & Christensen 2012), spatial redistribution of rainfall in China (Wu et al. 2009), and increased early winter snowfall in North America and Europe (Liu et al. 2012), among others. Large-scale consequences of Arctic sea ice decline have been linked to circulation and precipitation changes as far south as the tropics (Budikova 2009).

In spite of these powerful implications of Arctic change, there are significant general deficiencies in our understanding and modeling of Arctic climate processes. Recent model simulations of September sea ice extent used for the Intergovernmental Panel for Climate Change (IPCC) 5th Assessment Report (AR5) are informative of current sea ice predictive skill. Relative to models from the prior assessment (AR4 in 2007; Solomon et al. 2007), the ensemble mean rate of sea ice decline is somewhat closer to observations over the past couple decades (Stroeve et al. 2012). However, the large spread in model predictions has not changed, leading Stroeve et al. (2012) to conclude that, in spite of the additional six years of model development, AR5 and AR4 models are not substantially different. The IPCC AR4 report (Solomon et al. 2007) indicates that the large range in present-day and future simulations reduces confidence in model projections.

Some portion of this model spread may be related to the length of the summer sea ice melt season, which has been found to vary by up to four months among AR5 models, with most variability associated with the freeze up process for first-year ice (Mortin et al. 2014). Vertical mixing in the Arctic Ocean is uncertain in time, space, and mechanism (Krishfield & Perovich 2005), all of which can have profound impacts considering the substantial heat supply that resides in the deeper Arctic Ocean and the annual storage of solar heat in the upper ocean. Further, from a thermodynamic standpoint, differences in sea ice albedo among AR5 models contribute significantly to surface radiative budgets and likely also to the spread in predicted sea ice concentrations (Karlsson & Svensson 2013). The radiative effects of clouds have also been a longstanding problem in Arctic regions, yet the cross-model spread in Arctic cloud cover, phase, and condensed cloud water remains large and has not narrowed from AR4 to AR5 (Karlsson & Svensson 2013).

The AR4 report (Solomon et al. 2007) shed some light on these persistent model deficiencies and the apparent limited progress. That assessment noted that "Arctic climate is characterized by a distinctive complexity due to numerous nonlinear interactions between and within the atmosphere, cryosphere, ocean, land and ecosystems." Substantial natural variability in the Arctic coupled with the amplifying effects of interdependent feedbacks makes detection and attribution of Arctic change difficult. The AR4 report notes the "serious problem" associated with a lack of observational data appropriate for developing process-level knowledge and for assessing and developing models. Specific deficiencies are noted with understanding cloud, atmospheric boundary layer, sea ice, and upper ocean processes, and importantly the ways in which these are coupled. Additionally, as the Arctic transitions towards a new state dominated by first-year ice, much of our accumulated knowledge on an Arctic system dominated by multi-year ice may not be relevant for the future. With these major roadblocks, there is little surprise that progress towards characterizing Arctic change and improving model predictions is slow.

Yet progress must be made in understanding and representing these changing Arctic climate processes to better describe linkages with lower-latitude weather, improve sea ice forecasting, and develop the coupled-system models of the future. Kattsov et al. (2010) labeled Arctic sea ice change as one of the "grand challenges" in climate science and proclaim that concerted efforts are needed to obtain meaningful predictions of Arctic sea ice conditions in the coming decades. This grand challenge must be met with focused observational and modeling activities that aim to understand sea ice, atmosphere, ocean, and biogeochemical processes in a holistic, coupled manner.

### 1.2. Historical Background

The process of scientific discovery requires observation; thus, to understand the central Arctic climate requires one to go there. Long-term Arctic Ocean scientific field experiments have occurred since the drift of the *Fram* in the 1890s and the early works of Fridtjof Nansen, and others. Those initial scientific forays into the north provided valuable, first-order insights into the Arctic climate system and ecosystem. Over the ensuing decades advances in observing capabilities and a growing interest in global climate systems motivated the deployment of Arctic ice stations as part of the International Geophysical Year in 1957-1958, making fundamental observations of the Arctic atmosphere, ice, and ocean. Additionally, an ongoing series of Soviet/Russian North Pole drifting stations, beginning in 1937, has provided a long-term and unparalleled perspective of the Central Arctic climate system.

Sea ice is governed by two physical processes, dynamics and thermodynamics, which have been the foci of observational activities over the past few decades. In the mid-1970s, the Arctic Ice Dynamics Joint Experiment (AIDJEX) greatly advanced our understanding of sea ice dynamics and rheology via observations made at a continuous, year-long, interdisciplinary ice camp. Some 20 years later, the SHEBA program (Surface Heat Budget of the Arctic Ocean, 1997-1998; Perovich et al. 1999; Uttal et al. 2003) focused more on sea ice thermodynamics. It examined the surface heat budget of sea ice, again for a full year, and also targeted the ice-albedo and cloud-radiation feedbacks. SHEBA led to important findings on the relative impacts of different terms of the energy budget for multi-year ice, the role of cloud phase, and other topics. Among others, findings from SHEBA have been very influential on the treatment of sea ice in models. Ice camp studies such as SHEBA and others from the 1960s and 1970s also provided important opportunities to study central Arctic ecosystems over annual cycles (e.g., Melnikov et al. 2002; Ashjian et al. 2003; Sherr et al. 2003. The only winter study to examine biological processes across the entire ecosystem was the Circumpolar Flaw Lead study, which gave insight on topics from bacteria to beluga whales (Deming and Fortier 2011) and revolutionized previous conceptions of Arctic winter biology.

More recently, many activities were conducted in the Arctic Ocean during the 2007-2008 International Polar Year (IPY) and since that time. One large effort was DAMOCLES (Developing Arctic Modeling and Observing Capabilities for Long-term Environmental Studies), which combined field studies, an integrated monitoring system, and modeling to examine current Arctic conditions and explore the possibility of future reductions in ice cover. As part of DAMOCLES, an instrumented research vessel named Tara drifted with the ice pack for approximately one year. Results from DAMOCLES have been used to both validate and improve numerical models. One of the most recent drift stations occurred as part of the Norwegian N-ICE2015 project, which involved four distinct drifts north of Svalbard over a six month period onboard the RV Lance (Granskog et al. 2015). This project targeted new, thin ice and associated thermodynamic and dynamic processes.

The International Arctic Buoy Program has provided insight into sea ice motion and is a coordinating center for autonomous buoy activities targeting numerous objectives in the Arctic Ocean. One of the legacies of the IPY was the Arctic Observing Network. The Arctic Ocean portion of this international network consists of many autonomous drifting stations. These stations are deployed every year at the North Pole, in the Beaufort Gyre, and at other locations of opportunity, to measure time series of atmosphere, ice, and ocean properties. While buoy-based measurements have been quite successful for characterizing upper ocean, sea ice, some surface meteorology, and gas properties, such platforms have been less successful at measuring more detailed atmosphere and ecosystem information.

There have been many other programs with specific goals and shorter field campaigns, including icebreaker cruises, drifting ice camps, shorefast ice studies, aircraft campaigns, and coastal observing efforts. Studies have examined such topics as the marginal ice zone, primary productivity, ocean heat flux, springtime leads, ice drift, large-scale meteorology, low-level clouds, aerosol transport, airmass modification, stable boundary layers, and others. These efforts have provided valuable targeted information on specific properties and processes of the Arctic Ocean environment.

Additionally, since the late 1970s, satellites have been making routine observations of sea ice, upper ocean, and atmosphere properties on pan-Arctic scales. Passive microwave sensors that monitor ice concentration and extent have helped to document the decline of summer ice and the shift towards a younger ice pack. Laser and radar altimeters have more recently expanded capabilities towards measuring ice thickness, while techniques have been developed to track ice motion. Views from space also provide information on ocean productivity, particularly around the margins of the sea ice. In the atmosphere, satellite measurements have been used to compute radiative fluxes, observe the spatial distribution of clouds, and provide some profile information at course vertical resolution.

These past studies, and their contributions towards model development, have furthered our baseline understanding of the Arctic climate system. However, each of the past observational activities has key deficiencies that limit their utility for developing the kind of interdisciplinary, coupled-system knowledge that is needed to develop the models of the future. Many of these activities were narrowly focused to develop important, foundational knowledge within a given discipline; yet they lacked the interdisciplinary context and comprehensiveness that allows for a detailed understanding of coupling and feedbacks. Some of these activities were short in duration, offering snapshots of specific systems with little information on longer-term or inter-seasonal influences. Moreover, most studies were conducted in summer, when the central Arctic is more accessible, with relatively little attention given to winter. It is becoming increasingly recognized that the central Arctic climate system has memory and inter-seasonal and inter-annual linkages can play critical roles. Additionally, the spatial context has often been lacking, such that past campaigns have done relatively little to characterize the spatial heterogeneity and variability of different processes, or the scales on which they interact. This information is needed to achieve the necessary advances for current and future numerical model representations. And lastly, many of these observational activities were not in the "new" Arctic environment that is dominated by first-year sea ice. Instead these projects were largely representative of thick, multi-year ice that is becoming increasingly rare. Relatively little is known about the role of first year ice in the coupled atmosphere-ice-ocean system, yet this thin ice covers much of the Arctic Ocean and will play an increasing role in the future Arctic.

### 1.3. Programmatic Strategy

The present, evolving state of the Arctic system, against the backdrop of past Arctic research and knowledge, has motivated the MOSAiC initiative, which is being organized around the following underlying thesis:

> ***Multi-year, coordinated, and comprehensive observations, extending from the atmosphere through the sea ice and into the ocean in the central Arctic Basin are needed to provide a coupled-system, process-level understanding of the changing central Arctic physical, biological, and chemical system that will contribute towards improved modeling of Arctic climate and weather, and prediction of Arctic sea ice.***

This statement includes and implies a number of key strategic elements for MOSAiC. First, the program is organized around central Arctic ***sea ice*** and climate processes that affect its evolution, variability, and change. To understand this system, MOSAiC includes intensive, coordinated measurements that are appropriate for examining processes in great detail; in other words, MOSAiC is a ***process study***. Processes are often driven by ***cross-disciplinary*** linkages within the climate system. To provide the kind of multi-scale information that is needed to evaluate and develop coupled-system models, measurement activities are designed to characterize ***spatial heterogeneity*** in particular processes on scales that are appropriate for their representation in numerical models. Additionally, climate processes that affect the sea ice occur in all seasons, necessitating ***continuous year-round*** observations over at least a full annual cycle. Models provide a key means for interpretation, assimilation, and synthesis of knowledge; thus MOSAiC is guided by a ***full integration of modeling and observational activities*** from the beginning to ensure and facilitate the transfer of information between these perspectives. Lastly, due to the complexity of such a program and the broad regional interests, MOSAiC is an ***international endeavor*** that relies on a broad base of international participation, funding, and infrastructure.

## 2. SCIENTIFIC THEMES AND OBJECTIVES

At the top level, MOSAiC is organized around the broad science question:

***What are the causes and consequences of an evolving and diminished Arctic sea ice cover*?**

While more specific scientific questions and objectives are outlined in depth in the following sub-sections, there are important considerations about this high-level, guiding science question and the overarching approach to MOSAiC that warrant discussion here. These concepts cut across the science plan and serve as its general framework.

Sea ice acts as the central organizational element for MOSAiC. This is in large part because diminishing sea ice is a major fingerprint of Arctic change, and a "grand challenge of climate science" because of its complexity, uncertainty, and implications (Kattsov et al. 2010). ***Sea ice is an integrator of change*** in the Arctic climate system as it responds to variations in fluxes and forcings that occur via thermodynamics, dynamics, and other processes. Moreover, it serves as an important interface in a complex coupled Arctic system where it modulates the flow of energy, moisture, particles, and gases and provides a critical substrate for biological activity. The overarching MOSAiC science question includes some important specific words. "***Causes***" implies that sea ice is not the sole focus, but rather the climate system within which the Arctic sea ice resides is the focus, and in particular the interdisciplinary processes that interact with the sea ice over the course of its life cycle. In this regard, ***coupling*** and ***feedback*** among the many sub-systems of the Arctic (sea ice, atmosphere, ocean, biogeochemistry, ecology) are key considerations. "***Evolving***" implies that the system is not static, that processes can and do change as a function of season, location, and time. Lastly, "***consequences***" speaks to the fact that the changing Arctic, and evolving ice cover, feeds back on regional and global climate systems, biogeochemical cycling, and ecosystem structure and function in ways that are important to understand. Thus, larger-scale climate system linkages and implications for hemispheric weather are fundamental considerations for MOSAiC.

***Continuity*** is another extremely important concept. The Arctic climate system and sea ice environment has memory and inertia. The IPCC AR4 report states: "The thickness of sea ice is a consequence of past growth, melt, and deformation, and so is an important indicator of climatic conditions." Sea ice extent in September can be influenced by storm activity in preceding seasons (Screen et al. 2011). Similarly, atmosphere-ocean heat flux exchanges during fall freeze up are influenced by the extent and depth of ocean heating in the spring and summer and subsequent vertical ocean mixing (Jackson et al. 2010). Over the course of the year, the ice pack is continually evolving in response to seasonal cycles and episodic events imparted by the atmosphere and ocean. Thus, to understand any current state of the system requires understanding prior states. Additionally, the climate-relevant processes active in this system change over the annual cycle in response to seasonally-dependent conditions. Together these points support the need to study this system continuously over at least a full annual cycle.

The Arctic system is ***heterogeneous*** on many temporal and spatial scales. These scales differ among the atmosphere, ice, ocean, and ecosystem, can vary as a function of season or location, and as a function of specific processes. This inherent heterogeneity complicates our system-level understanding and our ability to represent it in models. Heterogeneity can be found in every sub-system and in most science questions targeting the Arctic climate system. Thus, an important aim of MOSAiC is to characterize heterogeneity to support model representations that permit similar variability on similar scales.

Coordinated with the top-level science question outlined above is a suite of sub-questions around which the specific observational and modeling activities of MOSAiC are organized. These include:

1) What are the seasonally-varying energy sources, mixing processes, and interfacial fluxes that affect the heat and momentum budgets of the Arctic atmosphere, ocean and sea ice?

2) How does sea ice formation, drift, deformation and melting couple to atmospheric, oceanic and ecosystem processes?

3) What are the processes that regulate the formation, properties, precipitation and life time of Arctic clouds and their interactions with aerosols, boundary layer structure and atmospheric fluxes?

4) How do interfacial exchange rates of biogeochemical process- related trace gases trigger the Arctic climate system?

5) How do sea ice and pelagic ecosystems respond to changes in Arctic sea ice?

6) How do ongoing changes in the Arctic climate system impact large-scale heat, momentum and mass fluxes and how do these changes feed back into the Arctic climate and ecosystem?

Each of these questions ultimately speaks to the changing Arctic ice pack and the influence it has on the climate system. Each is aimed at specific processes that are important in the central Arctic sea ice environment and each is guided by significant deficits in system-level understanding and model representation of these processes. Furthermore, all of these questions have an implicit bearing on large-scale processes that extend well beyond the local scale. Each specific question will be explored in more depth in the following sections where a basic knowledge is outlined and key gaps are identified.

## 2.1 What are the seasonally-varying energy sources, mixing processes, and interfacial fluxes that affect the heat and momentum budgets of the Arctic atmosphere, ocean and sea ice?

The heat and momentum budgets of sea ice are impacted by processes acting on the ice directly, in the atmospheric boundary layer, and in the ocean boundary layer, with extensive interactions among these three components.

### *Sea ice energy budget*

Energy fluxes that thermodynamically affect Arctic sea ice come from either the atmosphere or ocean. Many of these terms are illustrated in Figure 2.1, summarizing estimates of energy fluxes for an ice-covered Arctic Ocean system. This diagram demonstrates the complexity of the Arctic system, relative importance of processes, and intricate coupling among processes that leads to an approximately balanced sea ice energy budget. For context, it is important to consider that, in a steady-state system, the annual net energy flux to the sea ice should be 0 $W/m^2$, and an imbalance of 10 $W/m^2$ is approximately equivalent to an annual growth or melt of 1 m of sea ice. Moreover, Kwok & Untersteiner (2011) estimated that an excess of 1 $W/m^2$ in the net annual surface energy flux over the past 30 years can account for the observed reduction in sea ice extent and mass.

Uncertainty and spatial/temporal variability in individual flux terms can significantly impact our ability to understand this system and the mass balance of sea ice. The values specified in this diagram are obtained from many sources in different locations and times of year. Most are estimates from a past Arctic state that was dominated by multi-year ice (MYI). Thus, while there exist important uncertainties in the ability to determine each term under any condition, the uncertainties are likely even larger when attempting to represent the current Arctic system with more extensive first-year ice. Changes over the past 2-3 decades have likely altered the flow of energy through the system and the relative significance of various processes.

The atmosphere is a significant source of energy to the Arctic system and sea ice. Atmospheric transport from mid-latitude transient cyclones and quasi-stationary Rossby waves impinging on the Arctic Basin represents a large energy contribution. Consequently, the flux from these sources is similar to the net Arctic energy loss to space.

Atmospheric energy fluxes consist of upwelling and downwelling shortwave (SW) and longwave (LW) radiation, turbulent sensible and latent heat fluxes, and conductive fluxes through the ice. The annual net surface energy flux is positive, resulting in a net melting at the top of the ice. Atmospheric energy fluxes depend on characteristics of the atmosphere and clouds, surface type and roughness, surface albedo and others. Moreover, both atmosphere and surface characteristics vary in time and space due to many interdependent processes. Understanding this variability and how the processes combine to produce the net surface energy flux is key to understanding atmosphere-surface interactions over the Arctic Ocean.

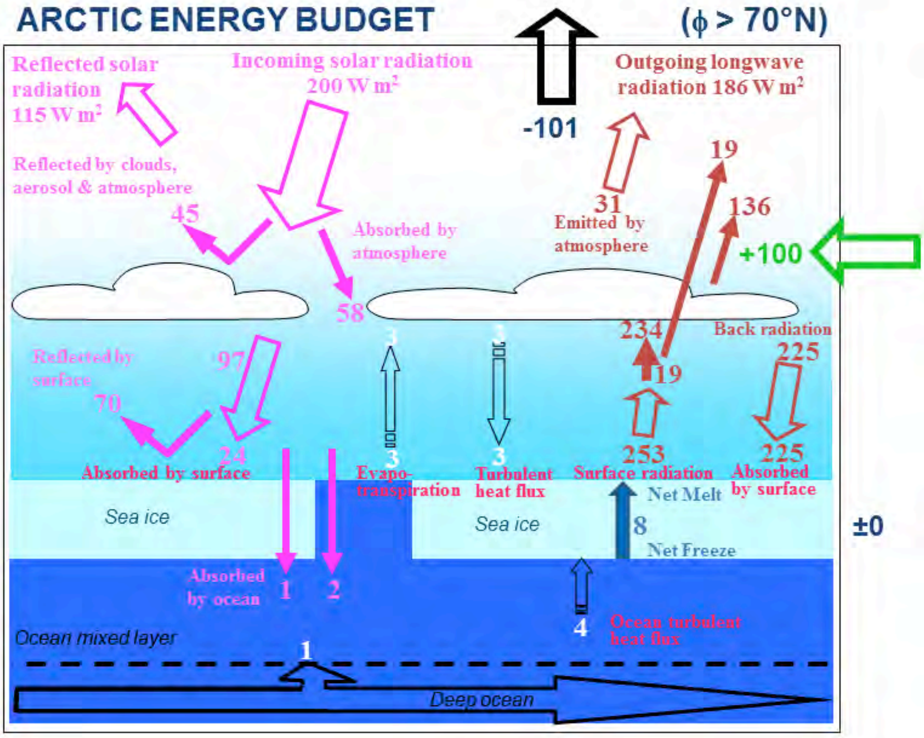


**Fig. 2.1**: Estimates of annual mean energy fluxes over a mostly ice-covered Arctic Ocean for a domain north of 70° N. All numbers are simply illustrative; they aim to demonstrate the order of magnitude but will vary substantially in space and time. Uncertainties in nearly all terms are large.

Energy passes through the ocean and/or ice surface interface in multiple ways and is believed to be a major contributor to thermal absorption and biological activity in the ice and upper ocean (e.g., Jackson et al. 2010, 2012). Transmission of solar energy through leads can be significant, depending on the open water fraction within the pack ice (Stanton et al. 2012). Transmission through MYI without snow was found to be larger than anticipated (~5 W/m$^2$) during the SHEBA summer (Light et al. 2008), and is even more important in first-year sea ice (FYI), which is thinner with different optical properties (Nicolaus et al. 2012). SW transmittance of 26 W/m$^2$ was observed for FYI in late summer when average over different surface types (Hudson et al. 2013). Longwave radiative processes, while always significant, become amplified when leads are present. The conductive heat flux through ice is theoretically in balance with the atmospheric and ocean heat fluxes and is dependent on the thermal contrast between ocean and atmosphere, and the thermal conductivities and depths of ice and snow. Conduction of heat from the warm ocean below is largely responsible for maintaining warm minimum surface temperatures over sea ice in winter (>-45°C) relative to surrounding Arctic land masses. While heat transfer at the surface interface has been examined in a many conditions, it has not typically been coupled with transfer processes happening within the atmosphere and ocean.

SW flux transmitted through snow/ice and into the ocean is the primary local source for the upper ocean mixed-layer heat budget. Optical properties of near-surface waters can affect where heat is stored in the upper ocean

(Granskog et al. 2015; Park et al. 2015). At the mixed-layer base there is a weak transport of heat upward from the deeper ocean via diffusive processes and intermittent events. Potential changes in upper ocean stratification related to altered density profiles may impact this ocean flux contribution and the upper ocean heat budget (e.g., Jackson et al. 2012). While not explicitly noted in Figure 2.1, advective heat sources within the mixed layer can be regionally important, generally near the marginal ice zone (Steele et al. 2010). This contribution may be increasing as the Arctic is now characterized by greater areas of seasonal ice and open water. Regardless of source, heat stored in the ocean mixed layer plays a critical role in the sea ice mass budget. An annual average ocean-to-ice turbulent heat flux of 3-8 W/m$^2$ has been suggested, with variability of 2 W/m$^2$ over scales of 100s of meters (Krishfield & Perovich 2005; Stanton et al. 2012), however these numbers are poorly constrained. The heat flux is dependent on upper ocean heat content, stratification, and the strength of turbulence. When balanced by typical conductive heat fluxes from the ice base, a deficit at that interface leads to net annual ice growth to balance the net ice loss at the top interface. As potential heat sources change, it is critical to understand how upper ocean heat budgets are transitioning.

Variability of energy fluxes in time is responsible for the annual cycle of sea ice growth and melt. The annual cycle of surface energy budget terms (Figure 2.2), as measured during SHEBA, illustrates some of the important energetic balances at play in the atmosphere-sea ice-ocean system. The surface emits LW radiation throughout the year, a process that is modulated by downwelling LW radiation from the atmosphere. While much of the solar radiation during sunlit seasons is reflected by the surface, the surface is warmed by SW radiation with some penetrating to warm the upper ocean. Conductive and sensible heat fluxes warm the surface in winter but are less important in summer, while the latent heat flux is negligible in winter but has a small cooling effect in summer. In winter there is a pseudo-balance where conductive flux of ocean heat from below, atmospheric sensible heat flux, and downwelling LW flux nearly offset the surface emission, resulting in a cooling that promotes sea ice formation. Ice melt occurs rapidly for 2-3 months in summer as the net atmospheric heat flux becomes more strongly positive and the upper ocean heat content increases substantially. The excess atmospheric flux at this time is largely due to increasing solar flux and the inability of the surface to respond via LW radiative, turbulent, and conductive fluxes because the surface temperature remains close to 0 °C (Persson 2012), as long as substantial amounts of ice are present. Heat storage in the upper ocean causes the peak in ocean-to-ice flux to occur a few weeks after the peak in solar insolation (Shaw et al. 2009; Hudson et al. 2013). These seasonal differences make it extremely important to understand the length of the melt season, as even small changes can lead to dramatic impacts on ice mass.

Short-term variability of the energy balance related to synoptic and mesoscale processes is significant. Three-day running mean surface radiative fluxes vary by 20-40 W/m2, and conductive and turbulent heat fluxes vary by 5-20 W/m2. Summer daily mean ocean-ice heat fluxes can range from near negligible to more than 80 W/m2, with heat fluxes at the bottom of the ocean mixed layer varying by an order of magnitude or more. Sub-daily variability related to transient events can often be much larger. For example, in late winter at SHEBA near-surface ocean turbulent heat fluxes temporarily reached 400 W/m2 during an event with very strong gradients in surface wind stress (McPhee et al. 2005), an order of magnitude larger than at other times during this campaign.

The complexity of the Arctic system is not only due to the numerous processes in the system but also to interdependence among these processes. An example is the wintertime response of the atmosphere-ice-ocean system to the presence of low-level mixed-phase clouds. These clouds has been linked to large-scale circulation bringing fluxes of heat and moisture from the south (e.g., Morrison et al. 2012; Mortin et al. 2015). When these clouds occur, the downwelling LW radiation increases substantially. This warms the surface leading to an increase in upwelling LW radiation but resulting in a net LW increase of 40 W/m2 or more. To compensate, the turbulent heat flux cools the surface and upward conductive flux of heat at the surface decreases. Convergence of conductive flux within the ice leads to the propagation of a warming signal down into the ice, diminishing the conductive flux at ice bottom, and potentially impacting bottom ice growth (Persson et al. 2016). Thus, the net impact on the system is not only determined by cloud radiative forcing but also by the response of other terms to the given perturbation. It is likely that these coupled flux processes may be changing as ice thickness, upper ocean structure, and other properties evolve in the new Arctic.

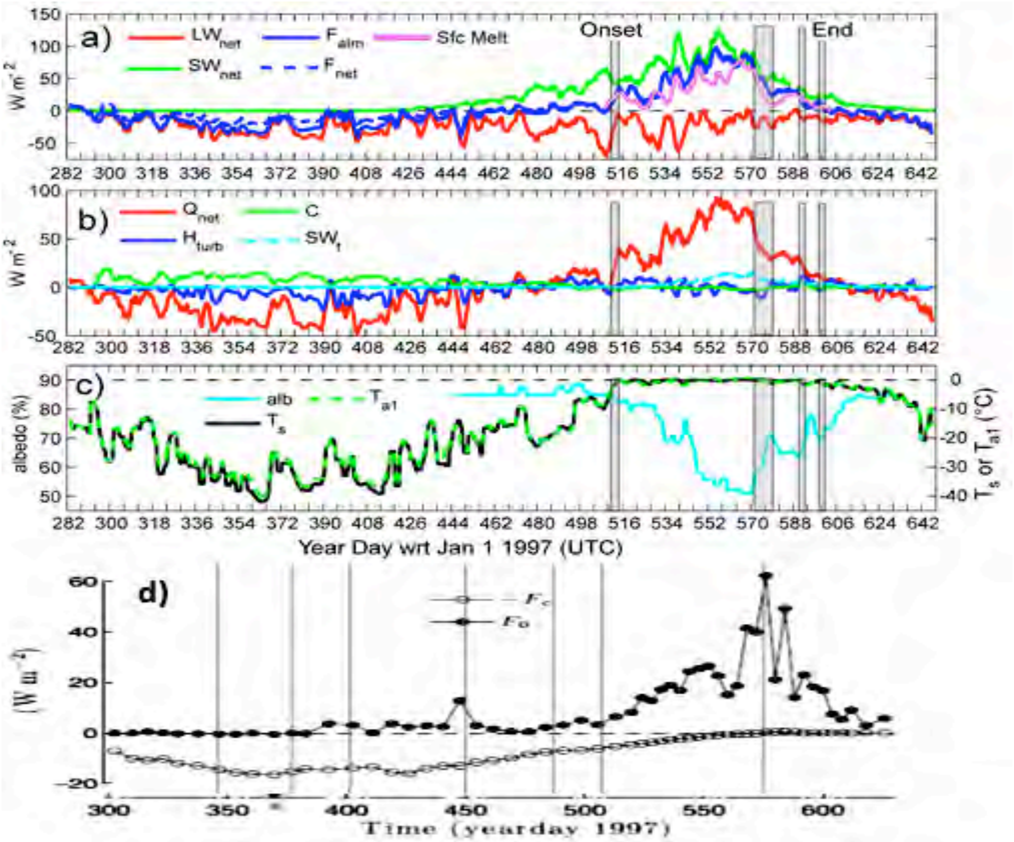


**Fig. 2.2:** Annual cycle of three-day running mean surface energy budget terms at SHEBA, including a) net LW, net SW, net atmospheric, and total surface flux; b) net radiative, net turbulent, and conductive heat fluxes and SW transmission; and c) surface albedo, surface temperature, and near-surface atmosphere temperature. The solid magenta line in a) shows the energy flux equivalent of the measured surface snow and ice melt (from Persson 2012). Panel d) gives the ocean-to-ice heat flux (black dots) over the same annual cycle (from Shaw et al. 2009).

To understand or model the sea ice system response to a forcing, numerous processes and their key parameters must be measured, understood, and well represented. A measure of how well processes are represented in a model can be found by examining how well the model can produce observed process relationships. Recent studies recognize the self-regulatory nature of these interdisciplinary process relationships for Arctic systems (Morrison et al 2012), continue trying to understand their dependencies (Sterk et al 2013), and have begun identifying model deficiencies through comparisons of process relationships in observations and models (Tjernström et al. 2005; Rinke et al 2012; deBoer et al 2012; Pithan et al 2013). MOSAiC observational activities must recognize the strong interdependence among the various interdisciplinary processes to understand surface energy interactions in the current Arctic.

### *Atmospheric boundary layer*

The structure and processes of the lower troposphere play an important role in atmosphere-surface interactions. Long-range transport of heat, moisture, momentum, and aerosols occurs aloft, and the extent to which these constituents interact with the surface depends on the thermodynamic and kinematic structure of the atmospheric boundary layer (ABL). The surface energy budget is also strongly impacted by the ABL structure, presence and properties of clouds, and availability of aerosols to form cloud particles. Hence, an understanding of the ABL, the occurrence of mixing events linking the ABL with the free troposphere or surface, and the interactions of these with external forcings such as synoptic weather events and large-scale circulation are crucial for understanding and modeling important low atmosphere processes. Unfortunately, none of these are well understood, particularly when considering the entire annual cycle and the changing Arctic environment. Limited measurements of the ABL structure and processes are available over the sea ice from a few periodic campaigns.

The central Arctic lower tropospheric structure is globally unique because of the perennial ice pack at the lower boundary. One primary and ubiquitous feature is the Arctic Inversion (AI) that typically occurs below 1.5 km (Figure 2.3), formed in part due to the relatively cold ice surface (Serreze et al. 1992). The AI depth is often larger over pack ice compared to coastal sites and tends to vary with synoptic activity, cloud cover, and proximity to open water, although the mechanisms controlling this variability are not clear and may be changing as the regional sea ice declines. All features also show substantial seasonal variability (Tjernström & Graverson 2009).

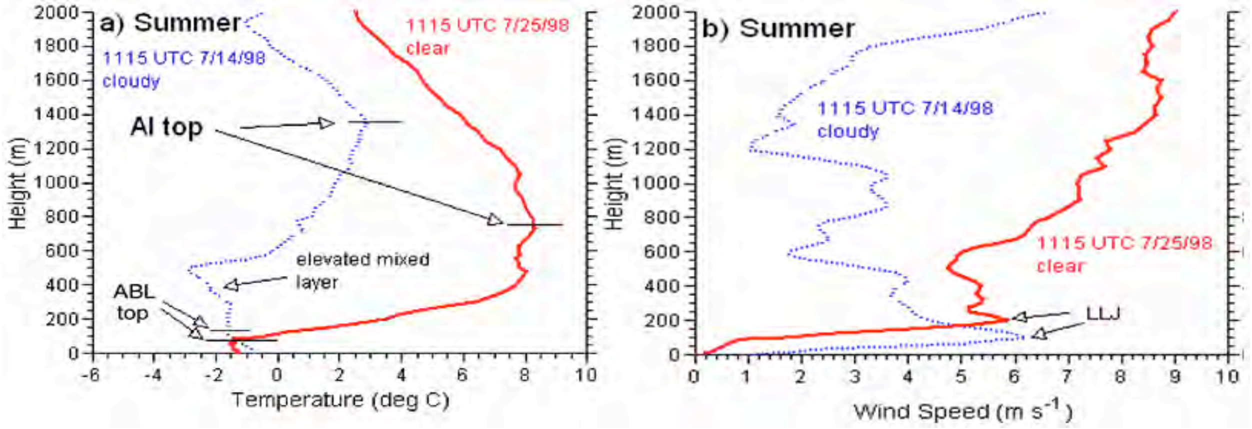


**Fig. 2.3**: Example summer temperature and wind profiles in the lowest 2 km at SHEBA for clear (red) and cloudy (blue) conditions. The Arctic inversion (AI), atmospheric boundary layer (ABL), and low-level jets (LLJ) are labelled.

The ABL is the layer extending up from the surface that is mixed by near-surface buoyant or mechanical processes, and thus is the layer directly responsible for interactions with the surface. The depth and properties of this layer depend on season, surface properties, and the atmospheric state aloft. The ABL structure is dominated by two regimes; either near-neutral (adiabatic) and capped by an elevated temperature inversion or stably stratified within a surface inversion. The latter is most common in winter while summer is dominated by elevated inversions capping a well-mixed ABL. When optically thick low-level clouds occur, a cloud-driven mixed layer (CML) resulting from “upside-down convection” driven by cloud top radiative cooling (Morrison et al. 2012) is observed extending from cloud top to a few hundred meters below cloud base. This CML is often distinct from the ABL below, but sometimes couples with it (Shupe et al 2013). Although the processes responsible for this coupling state are not entirely clear, it is important for vertical transport of moisture, aerosols, and other atmospheric constituents. Both surface-based ABL and elevated CML interact with the AI and modify its thermal structure and stability through local surface and cloud processes.

The stability and depth of the AI presents a significant impediment to vertical transport of heat, moisture, momentum, and aerosols among the free troposphere, cloud level, and surface. However, evidence for mixing events in the lower troposphere was found in several field programs. For example, during IAOE-91 sudden changes in near-surface cloud condensation nuclei (CCN) concentrations were frequent, despite the long distances from significant sources (Bigg et al 1996), suggesting changes in mixing between otherwise stratified layers of aerosols. Further evidence suggests that vertical mixing and transport can occur via processes related to low level jets (LLJ), cloud-driven processes, and larger-scale processes related to baroclinic fronts (Tjernström & Mauritsen 2009).

Low level jets can be common features throughout the year over the sea ice (Tjernström et al. 2004) that play a role in turbulence, mixing and stratification processes in, and near, the ABL. These often have wind velocities that are only 2-3 m/s faster than the free-stream wind above and are believed to be caused by inertial oscillations in a layer that becomes decoupled from the surface by stable stratification below (Andreas et al. 2000). Thus, such jets tend to accompany transitions in low-level mixing state and depth. Baroclinicity near transient cyclones was the primary forcing for LLJs observed during the Tara drift in the Central Arctic (Jakobson et al. 2013). Such baroclinicity and coupling state transitions appear to be common in the Arctic lower troposphere, and may be particularly common near the MIZ where LLJ properties may vary with baroclinicity and ice-edge relative wind direction (Langland et al. 1989).

Frontal passages can also impact lower tropospheric processes by driving changes in vertical mixing and the origins of air masses. For example, during AOE-2001 high-resolution temperature profiles showed transitory warm pulses extending to the surface from the free troposphere at times of synoptic or mesoscale frontal passages (Tjernström et al 2004). Such events increased near-surface turbulence and impacted surface temperatures. Similarly, vertical exchange mechanisms within the ABL can be influenced by the passage of "microfronts" (Tjernström & Mauritsen 2009).

The vertical flux of momentum from the atmosphere to the surface, or wind stress, is a key atmospheric process affecting the movement of sea ice. Ice movements on all time scales are strongly correlated with the near-surface wind and wind stress (e.g., Thorndike & Colony 1982). Surface stress is affected by lower tropospheric wind and turbulence, near-surface stability, and surface roughness (e.g., Zhang et al. 2013). Surface roughness is a function of surface type and heterogeneity, and is generally higher in the presence of more numerous ice floe edges (Andreas et al 2010) or in regions of significantly deformed ice. Stress is asymmetrically distributed among the sides of a storm (Persson et al. 2005), which may impact the net sea ice advection. Furthermore, mesoscale deformational features of the low-level wind field, including those produced by atmospheric fronts (e.g., Wakimoto & Murphey 2008) and divergence due to surface roughness gradients, may lead to divergence in sea ice drift (Brümmer et al 2008). Clearly, transient cyclones have a significant impact on sea ice evolution (Kriegsmann & Brümmer 2014). Data to quantify the interplay of wind forcing mechanisms, stability, and surface heterogeneity for modulating the surface stress and sea ice movement is generally not available.

In general, further clarification of the Arctic lower troposphere structure, processes, and variability is needed, particularly related to: atmospheric interactions with surface forcing; vertical mixing of moisture, heat, momentum, and aerosols; LLJ processes; cloud processes; and spatial/temporal evolving structure of the AI. Furthermore, there is very little understanding of how these processes and their interactions are modulated by synoptic and mesoscale forcing, by the seasonal lack of diurnal variations, by surface heterogeneity, and by long-term changes in surface characteristics, such as the recent increase in FYI. In addition, observations near the ice edge suggest that the lower-tropospheric structure is greatly modified in this region in ways that are not well understood but of clear significance because of the temporal and areal increase of the MIZ in the new Arctic Ocean.

### *Ocean boundary layer*

The central Arctic upper ocean plays a critical role in annual and long-term evolution of the sea ice. It is an interface linking atmosphere, sea ice, and deep ocean energy fluxes. Importantly, while there are many similarities between ocean and atmosphere boundary layers, the ocean has distinct time and length scales, and the potential to store heat over longer periods and thus uniquely influence the seasonal evolution of sea ice energy budgets. Heat fluxes from ocean to ice are responsible for more than half of the net sea ice melt during a given year (Perovich et al. 2003; Steele et al. 2010). Upper ocean processes may be sensitive to regional changes that impact freshwater budgets, open water fraction, surface stress, and others. Thus, it is a high priority to fully characterize the upper ocean structure, stratification, mixing processes, transfer of heat and mass, and the role of transient events. This needs to be seen in the context of a new Arctic system and in relation to other coupled systems.

The Arctic Ocean vertical structure is comprised of multiple stratified layers (e.g., Figure 2.4) that evolve with season. As a result of less surface evaporation and relatively more freshwater input from rivers, the upper Arctic Ocean is particularly fresh compared to other oceans. Arctic Ocean waters are also cold due to strong cooling for most of the year and due to interactions with sea ice. The vertical salinity structure is most influential on density, leading to one or more important haloclines that stratify the upper ocean. Atop the uppermost halocline is the ocean mixed layer (OML), typically less than a few 10s of meters thick, where temperature, salinity and other properties are well mixed by turbulent processes. Due to strong interactions with the atmosphere and the ice above, the OML heat budget has a large seasonal cycle. To understand the impact of this OML on sea ice thermodynamics requires an understanding of heat fluxes into this layer, from above via atmospheric fluxes through open water and snow/ice, from below via entrainment processes, and laterally by horizontal advection. Trough, the OML wind stress is transferred into the ocean causing turbulence, vertical mixing, and waves.

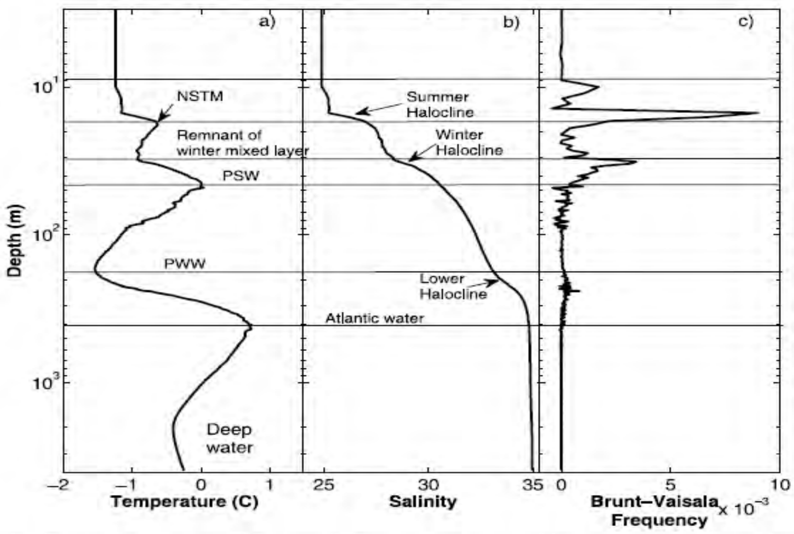


**Fig. 2.4:** Vertical ocean structure in Canada Basin including (a) temperature, (b) salinity, and (c) Brunt-Vaisala frequency profiles. NSTM=near surface temperature maximum. PSW=Pacific summer water. PWW=Pacific winter water.

Decoupled from the OML by a relatively strong halocline, vast reservoirs of heat exist at moderate depths in the Arctic Ocean. These are fed by the inflow of warm, salty waters from the North Atlantic (Schauer et al. 2002), and to a lesser degree the North Pacific. The somewhat fresher Pacific waters are generally shallower, leading to potentially enhanced heat fluxes towards the surface, yet their influence is limited largely to the Amerasian Basin with only intermittent impact beyond. While ample ocean heat exists to melt all sea ice, the typical flux of deep ocean heat into the OML is small (on average <1 W/m$^2$, e.g., Shaw et al. 2009). Much of this flux occurs via transient events (McPhee et al. 2005; Hudson et al. 2013) or in specific geographic locations. However, it is critical to consider these processes as intermediate depth Arctic Ocean warming (Polyakov et al. 2010). Potential changes to upper ocean stratification and mixing can have strong impact on the heat budget of the upper-ocean and the sea ice.

The stratified upper ocean undergoes important seasonal cycles in temperature and salinity that interact with sea ice. In late spring and summer, the ocean heat content increases as sun angles increase. Surface transmission increases due to melted snow and enhanced lead formation (Stanton et al. 2010). While solar input is the dominant source of upper ocean heat (Krishfield and Perovich 2005), the ocean heat content maximum lags the solar cycle by a few weeks due to ocean heat storage and lateral advection (Steele et al. 2010). Ice melt during the summer/fall season freshens the OML, strengthens the halocline, and decouples the OML from deeper waters. Ocean heat fluxes leading to bottom ice melt persist longer into the fall than top melt, but eventually OML temperatures cool to the freezing point and ice formation commences. During the ice-growth season the OML slowly becomes saltier (ice brine rejection), which diminishes the strength of the halocline, deepens the OML, and increases the potential heat fluxes associated with transient events. Weak ocean-to-ice heat fluxes persist through winter, indicating that heat stored deeper down in the water column continues to be mixed upward.

An interesting and emerging feature of the upper ocean structure, and a potentially important mechanism for storing heat that will be eventually accessible to sea ice, is the near surface temperature maximum (NSTM, Jackson et al. 2010; see Figure 2.4). This feature occurs as solar radiation is absorbed in the upper ocean through leads, melt ponds, and the ice (McPhee et al. 1998), while the summer halocline strengthens and shoals. This process traps heat at depth (Hudson et al. 2013) and can be supported by ice melt. In turn, this results in more transparent waters allowing deeper penetration of SW radiation (Granskog et al. 2015). Recent studies suggest that the NSTM may persist through multiple seasons (Steel et al. 2011). Spatial variability in NSTM structure and summer halocline depth and timing suggest influences from Ekman pumping, storms, advection, latitude, local ice conditions, factors controlling solar input, and others (Jackson et al. 2010). The spatial distribution and manifestation of this feature has not yet been established, but where present it can have a significant impact on fall freeze up and the release of stored heat. Clearly, the dynamics and thermodynamics of the NSTM must be considered when representing and modeling central Arctic climate.

There remain many critical and important areas of research regarding the accumulation and vertical transport of ocean heat. For example, while the un-disturbed Arctic Ocean tends towards stratification, periodic storm-driven mixing processes can weaken the stratification and cause the release of deep ocean heat into the OML and towards the surface (e.g., Hudson et al. 2013). However, it is unclear how these storms manifest and generate turbulence in a thinner ice environment, and how they interact with features like the NSTM. In fully ice-covered conditions, previous investigations (Levine et al. 1985; D'Asaro & Morison 1992; Rainville and Winsor 2008) also point to weak internal waves and mixing, and both appear to strengthen with decreasing ice cover. Thus, it is important to gain a better understanding of the spatial and temporal distribution of ice roughness lengths and how these drive OML turbulence in response to storms and other ocean dynamical processes. Similarly, long-lived ocean eddies and sub-mesoscale fronts can play key roles in heat transfer at the halocline (Fox-Kemper et al. 2008; Mahadevan et al. 2012), but important questions remain regarding their formation mechanisms, movement, and regional impacts (Timmermans et al. 2008). Furthermore, double-diffusion has been proposed as a mechanism for transporting Atlantic Water heat vertically in regionally specific locations (e.g., Rudels et al. 1999), but its net effect on the sea ice system has not been established.

The overall partitioning of OML heat budgets is also uncertain due to spatial and annual variability. For example, it is critical to understand the partitioning of solar heating as a function of open water fraction, melt pond fraction, ice thickness, snow depth, and other key parameters. In this regard, it is also necessary to determine the relative influences of ice dynamics (e.g., Stanton et al. 2012) versus thermodynamics (e.g., Steele et al. 2010) in controlling the open water fraction and ocean heat content. Similarly, while it is expected to be small in the central Arctic, it is not clear how far the advection of heat within the OML from the MIZ extends into the pack ice, and how this is changing as the seasonal ice zone expands. Lastly, with such a large potential impact, it is important to determine the partitioning of vertical heat fluxes into the OML, specifically the relative influences of weak, persistent entrainment processes versus the periodic but stronger impact of baroclinic storms.

As the Arctic ice pack continues to evolve numerous potential process-level changes must be explored. For example, there are indications that the OML has become fresher (Rabe et al., 2014), leading to stronger stratifying haloclines, and the NSTM has strengthened (e.g., Toole et al. 2010; Jackson et al. 2010). At the same time there is a suggestion of a slow increase in the basin-wide ocean-to-ice heat flux (Krishfield & Perovich 2005). While these changes might be expected as a result of the thinning ice pack, it is yet to be determined how the net OML heat budget is adjusting in response. The broader implications of this changing upper ocean stratification must also be explored through impacts on vertical mixing of deeper ocean, nutrient-rich waters that are important for upper ocean productivity (e.g., Jackson et al. 2010).

## 2.2 How does sea ice formation, drift, deformation and melting couple to atmospheric, oceanic and ecosystem processes?

### *The importance of sea ice dynamics*

As outlined above, many of the physical processes that govern the thermodynamic growth and melt of sea ice are still only crudely understood and as such only crudely represented in models. The same holds for sea ice dynamics, which describe the movement of the ice pack in response to atmospheric and oceanic forcing. In particular, for the younger and thinner ice cover that is typical of today's Arctic, little observational data of the detailed functioning of sea ice dynamics is available. This limits our ability to represent important aspects of sea ice dynamics in current models. One central aim of MOSAiC is to improve our understanding of sea ice dynamical processes, and in particular to shed light on key differences between strong multi-year sea ice cover relative to the much softer, more deformable sea ice cover that is typical for large parts of the Arctic today. Ice dynamics observations and studies are also needed to improve our understanding of observed changes in sea ice drift speed on different time scales (Spreen et al. 2011; Kwok et al. 2013).

The importance of sea ice dynamics for the overall evolution of the Arctic ice pack derives from three main processes: First, sea ice dynamics continuously deform the ice pack and create areas of open water, permitting direct atmosphere-ocean interactions. In winter, this open water fosters further ice formation, while in summer these areas warm rapidly and increase melting of surrounding ice. Second, sea ice dynamics export sea ice from the Arctic and hence continuously diminish the existing ice cover. It has long been known that without a representation of these processes in models, a realistic simulation of the global sea ice cover is impossible. Model simulations without sea-ice dynamics consistently result in a larger sea ice volume (e.g., Owens & Lemke 1990) and a decreased sensitivity of the ice pack to climatic changes (Hibler 1984; Vavrus & Harrison 2003) compared to models that include ice dynamics. Third, sea ice dynamics result in ice deformation, and with that a change of ice surface characteristics. Ridged and rafted sea ice (e.g., Hibler et al. 1972; Timco & Burden 1997; Läpparanta et al. 1995; Høyland 2002) has substantially different surface roughness, surface properties and thickness than level ice. Snow accumulation and redistribution is also different, as is the preconditioning for summer melt ponds. Consequently, ice dynamics thus affects the surface energy balance and freezing/melting processes. Ridges in first-year ice are different in their properties and degree of consolidation, compared to ridges in multi-year ice. From an observational point of view, the surface roughness of sea ice also critically affects the response of SAR satellite sensors.

Despite decades of related research, models still have difficulties in realistically representing the observed motion of sea ice. Studies have found, for example, discrepancies between model simulations and observations in the seasonal cycle of sea ice drift speed, in the long-term trend of sea ice velocity (Rampal et al. 2009), in Fram-Strait sea ice export (Langehaug et al. 2012), and the location and strength of large-scale circulation patterns (Kwok 2011). As outlined below, these discrepancies are probably as much an issue related to modelled ocean and atmosphere forcing as they are to limited physical understanding and representation of the governing physical processes in the sea ice model itself. Detailed, inter-disciplinary measurements in the central ice pack will shed light on the underlying causes of discrepancies in a coupled ice-atmosphere-ocean system, and provide data and insights that will help to reduce them in next generation of Earth System Models.

### *Oceanic and atmospheric momentum transfer to sea ice*

An improvement of the representation of sea ice dynamics in models depends on a realistic simulation of, and coupling to, atmospheric and oceanographic forcing. More realistic simulations are expected to arise from the more detailed understanding of atmospheric and oceanographic processes that MOSAiC will provide, in particular with regard to processes such as decoupling of surface winds from winds aloft in the very stable stratification that sometimes occurs in the Arctic. In addition to a better understanding of the forcing itself, however, the interaction of the forcing with the ice pack must also be more realistically represented in numerical models. Such realistic representation is, unfortunately, still hindered by a lack of sufficient data and understanding, in particular for first-year sea ice.

One of the key foci of MOSAiC is therefore a better understanding of the evolution of sea ice roughness with a focus on differences between first-year and multi-year ice. In current models, the drag coefficient that couples sea ice mechanically to the ocean and atmosphere is often taken as constant throughout the entire ice pack, independent of ice age. A younger ice cover that has not undergone the substantial deformation (in particular ridging) that is typical for thick multi-year ice will, however, be much smoother than multi-year ice. Therefore, a statistical representation of roughness length throughout the entire life cycle of first-year ice, similar to past representations of multi-year ice, is highly desired. This will allow for a more realistic representation of the drag coefficient in model simulations, in particular if these include a sub-grid scale ice-thickness distribution.

Another critical need is a better understanding of the evolution of floe size in today's thin ice pack. A realistic parameterization of the floe-size distribution in models is important for the representation of lateral melt, but also for the lateral transfer of momentum. In particular, for the oceanographic momentum forcing, the lateral forcing as described by a floe's form drag can account for more than half of the total momentum transfer (Lu et al. 2011). Currently, there is little understanding of how the evolution of floe size differs for thin, first-year ice compared to thick multi-year ice.

### *The response of sea ice to momentum forcing*

Even more than the mechanical forcing itself, the response of the ice pack to a given forcing depends crucially on ice type, thickness, and strength. The resulting properties are described by the rheology of the ice pack, which relates internal stresses to the resulting strain of the ice pack. This rheology determines the response of the ice and underlying ocean to wind forcing (Martin et al. 2014). The de-facto standard for the representation of sea ice rheology in numerical models is a viscous-plastic formulation (Hibler 1979), or its numerically more efficient derivative, the so-called elastic-viscous-plastic formulation (Hunke & Dukowicz 1997). For both formulations, the original elliptical yield curve is usually applied, which allows models to simulate observed large-scale dynamic features of the ice pack. Many observed aspects of ice deformation are, however, not realistically captured by current models based on these rheologies (e.g., Kwok et al. 2008; Girard et al. 2009), although it is still unclear if the differences between simulations and observations are directly related to the rheology itself or only to its specific formulation. A possible explanation of shortcomings of these classical rheologies is related to their underlying assumption that the ice cover can be treated as a continuum. While this assumption was justified for large grid-cell sizes typical for earlier models, it becomes increasingly violated as grid resolution increases.

Multi-scale measurements in the central Arctic ice pack will allow both improved understanding of the functioning of sea ice rheology and its representation in models. A particular priority is to establish a robust, statistical distribution of ice-drift velocities in a non-uniform ice pack that is exposed to a similar atmospheric and oceanographic forcing. This then allows for detailed quantification of the ice response to different concentrations and thicknesses in particular in an ice pack that is comparably thin. These measurements will complement similar past measurements in thick, multi-year ice, such as during the AIDJEX campaign in the 1970s (Untersteiner et al. 2007). A synopsis of these measurements will then provide a robust data set against which to assess the quality of improved model formulations. A particular focus of such improved model formulations should be on realistic representation of movement and deformation of thin ice, including a parameterization of cohesion. Currently, most related parameterizations either fully neglect these processes or are based on thick, multi-year ice. These parameterizations are thus based on an ice cover that is, in bulk, less viscous than an ice cover primarily made up of first-year ice. In particular, the current parameterizations usually do not capture processes such as rafting and fingering that occur in thin ice.

Another set of features that is not realistically represented in current ice models is the formation of leads. These have long been known to be crucial for proper representation of heat exchange between the ocean and atmosphere (Maykut 1978), but are usually crudely parameterized in large-scale models. There has been progress in modelling the interaction of leads with the atmospheric boundary layer using Large Eddy Simulations (Lüpkes et al. 2008), but a realistic representation of the lead distribution is still largely lacking. To address this gap ultimately requires realistic representation of the cohesive strength of ice, which is largely lacking for young, thin ice. A representation of leads will also profit from improved observation techniques such as gliders, AUVs (e.g., Doble et al. 2009) and ROVs (e.g., Nicolaus & Katlein 2013) in the ocean and UAVs (e.g., Ramana et al. 2007) in the atmosphere, which allow for a more detailed study of the role of leads for air-ice-sea interaction than has been possible in the past. Such in situ measurements combined with the upcoming availability of lead climatologies from satellite remote sensing (Broehan & Kaleschke, in prep.) will allow dedicated modeling studies to be evaluated against reliable data sets both on the small scale covered by MOSAiC and the large scale covered by satellites.

*Sea ice - wave interaction*

Another important aspect of sea ice is its interaction with waves. While there has been long-standing research on the topic (Squire et al. 1995), the increased extent of the marginal ice zone, thinning of sea ice, and movement towards ice models with higher resolution and more detailed representation of small-scale heat exchange processes have recently renewed scientific interest in ice-wave interactions. Such interactions are important because the background wave field largely determines floe size and floe clustering in the marginal ice zone and is crucial for realistic modeling of heat and momentum transfer among the ocean, atmosphere, and ice. Recent instrument developments (e.g., Doble et al. 2006) allow for quantifying wavefields and the ice response with high temporal and spatial resolution. The philosophy of MOSAiC to follow young sea ice across its entire life cycle will offer insights into sea ice – wave interactions that are hard to achieve in shorter field settings. In particular, by monitoring the temporal evolution of the wave field outside and within the ice pack, we can deduce a detailed relationship on how much sea ice of varying thickness and concentration interacts with the wave field. Also the reverse mechanism, the breakup of the ice pack by external wave action can be studied.

### 2.3 What are the processes that regulate the formation, properties, precipitation and life time of Arctic clouds and their interactions with aerosols, boundary layer structure and atmospheric?

Clouds play at least three noteworthy roles in the climate system. They interact significantly with atmospheric radiation, which impacts top-of-atmosphere radiative balance, the surface energy budget, and the vertical distribution of radiative heating within the atmosphere. Second, clouds are an essential link in the hydrologic cycle by transporting and transforming atmospheric moisture into precipitation. Finally, as a result of these radiative and latent heat processes, along with associated, cloud-driven dynamical mixing, clouds modulate atmospheric vertical structure. Importantly, these climate system interactions occur on multiple scales in time and space, and clouds participate in a number of important feedback processes (e.g., Curry et al. 1996; Stephens 2005).

To first order, Arctic clouds can be distinguished into three basic categories.

1. Low-level (<2 km) stratiform clouds or fog: These clouds typically contain liquid water at super-cooled temperatures, and are often mixed-phase, containing both liquid and ice. They are largely supported by cloud-scale feedbacks (Morrison et al. 2012), which contribute to their spatially-extensive and persistent nature. By containing liquid water, they are responsible for strong radiative effects on the surface (Shupe & Intrieri 2004). However, they are only weakly precipitating as a result of slow, but persistent ice crystal production.

2. Synoptic storms: These storms are typically comprised of a collection of clouds within an organized, mesoscale system that is energetically-linked to the large-scale flow (e.g., Inoue et al. 2010). Cloud tops often extend above 4-8 km. These cloud systems have abundant ice production and can contain embedded mixed-phase regions. Thus, they are responsible for the most intense precipitation events in the Arctic. In some cases, these systems can have strong impact on surface radiation due to their depth and high total condensed cloud mass.

3. Quiescent ice clouds: Due to typical temperatures, layers of ice crystals can occur at any height within the Arctic troposphere ranging from high-level cirrus to near-surface diamond dust. Being comprised solely of ice crystals, these clouds usually have a weak interaction with atmospheric radiation and thus have a small impact on surface energy budgets (e.g., Intrieri & Shupe 2004). As a result, they also have weak dynamical effects and typically do not contribute much net precipitation at the surface.

Clouds, and cloud parameterizations, have been shown to play critical roles in Arctic and global model studies. Model radiation budgets have a strong sensitivity to the details and sophistication of cloud parameterizations (Gregory and Morris 1996; Rotstayn et al. 2000). Holland & Bitz (2003) indicated that increases in cloud cover are significantly correlated with amplified Arctic warming signals, while Vavrus (2004) suggest that half of the Arctic warming response to greenhouse gas forcing is related to increases in clouds. One of the strongest global impacts in $CO_2$-doubling experiments is seen in the partitioning of high latitude cloud phase (Tsushima et al. 2006). Further, Vavrus et al. (2009) found that the models that best represent present day cloudiness tend to predict future increases in clouds in response to typical prescribed greenhouse gas forcing scenarios.

In spite of the prominent role clouds play in both the real and modeled worlds, models continue to struggle with representing cloud-processes. Clouds and cloud feedbacks are the largest contributors to uncertainty in our understanding of climate sensitivity (IPCC 2007; ACIA 2005). Additionally, the indirect effects of aerosols on clouds are cited as a climate system forcing that has a very low level of understanding (IPCC 2007).

Model deficiencies cut across models at all scales. Global models evaluated against Arctic observations show a poor representation of cloud phase as a function of height and misrepresent the total condensed cloud mass (de Boer et al. 2012), with particularly large cross-model spread in winter (Karlsson & Svensson 2011). The implications of these difficulties were revealed by an evaluation of Arctic regional atmospheric models against SHEBA observations. Surface broadband radiative fluxes were represented reasonably well under clear skies; however, with clouds present the spread of model errors widened and, more alarmingly, net deficits of 10-25 $W/m^2$ appeared in all models (Figure 2.5; Tjernström et al. 2008). These cloudy-sky biases coupled with high cloud occurrence fractions can have profound effects on the surface energy budget, and were found to impact the timing of ice melt (Inoue et al. 2006). Thus, it is not surprising that basic parameters such as the surface albedo must be tuned to achieve the approximate correct surface energy budget and sea ice mass (Uotila et al. 2012). Furthermore, the spread in 21st century model runs with regard to low-level clouds is large (Vavrus et al. 2009), suggesting uncertainty in models' abilities to represent clouds in a future changing climate.

The primary deficiencies and uncertainties exposed by these studies reside in some of the fundamental physical processes of the system: the partitioning of phase, sustaining supercooled liquid water in the presence of ice, representing cloud dynamical responses, and capturing the interactions among clouds, boundary layer, aerosol, radiation, and surface processes. Even single-column and cloud-resolving model studies (e.g., Klein et al. 2009) demonstrate these difficulties. For example, many large-scale models partition cloud phase as a simple diagnostic function of temperature, while observations clearly show that temperature alone cannot explain phase variation (Turner 2005; Shupe et al. 2006). In general, model deficiencies are associated with the inability to resolve and/or parameterize the important cloud-scale dynamical and microphysical processes that lead to vertical and horizontal separation of liquid and ice phases at relatively small scales. To some degree these problems also result from poor understanding of cloud-aerosol interactions, with little knowledge of the background concentrations that are present and the nucleation modes that are active.

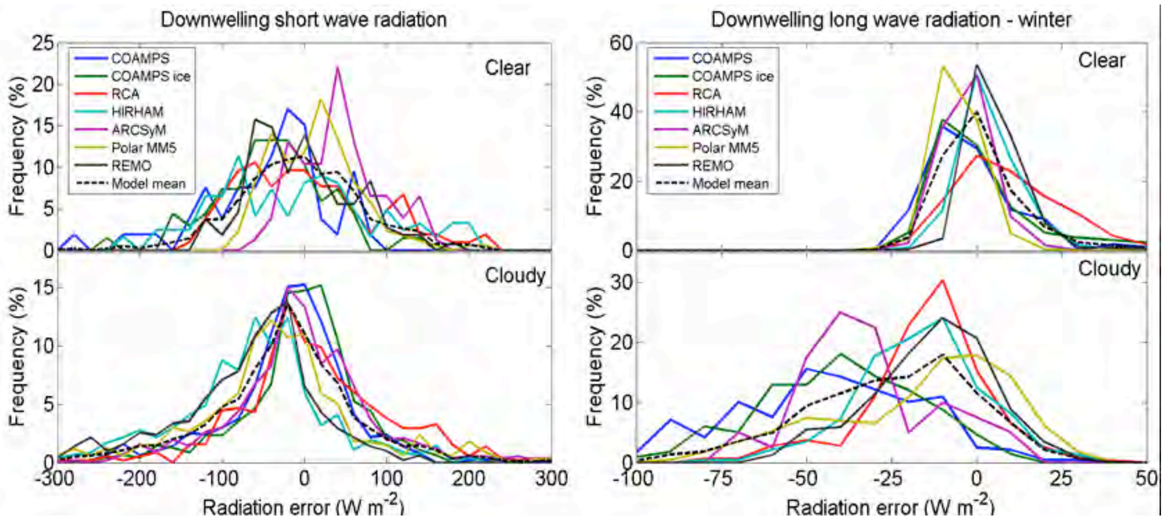


**Fig. 2.5**: PDFs of model error relative to SHEBA observations of (a) summertime SW radiation and (b) wintertime LW radiation, for clear (top) and cloudy (bottom) conditions. Data are included when models and observations agree on the presence or absence of clouds. After Tjernström et al. (2008).

A significant driver of the large uncertainties associated with clouds, particularly in the central Arctic, is a general lack of observations (IPCC 2007). Most past efforts to observe Arctic clouds have been near coastal locations. These include fixed ground-based Arctic coastal stations (e.g., Barrow, Ny Ålesund, Eureka, etc.) with operational cloud observing instrumentation (Shupe et al. 2011) and near-coast aircraft cloud campaigns (Herman & Curry 1984; Verlinde et al. 2004; Bierwirth et al. 2013). While these observations helped to elucidate many Arctic cloud properties, there is a particular dearth of cloud observations over the central Arctic sea ice. Detailed, cloud profiling has occurred during periodic ship-based (SHEBA, AOE2001, ASCOS, etc.) and aircraft (BASE, FIRE-ACE, ACCACIA, etc.) campaigns over the sea ice. Of these few observations, many are limited in duration and season (warm season bias), and many lacked detailed accompanying information on BL structure, surface characteristics, and aerosol properties. For the later, there is little information on aerosol composition, seasonal and spatial variability, and ice nucleation ability, particularly at cloud levels. While clouds are a major global uncertainty, even less is known about Arctic clouds relative to those elsewhere on Earth, due to logistical constraints and difficult conditions for making observations in that region.

Cloud studies will be a critical element of MOSAiC. Importantly, these studies must target the processes that fundamentally control phase partitioning, longevity, precipitation, and interactions with the atmosphere, aerosols, and surface. Many of the process-level issues related to clouds, and which lead to many of the identified modeling deficiencies, will be outlined here.

Cloud phase is an important control on many cloud processes because of fundamental differences between populations of liquid water droplets versus ice crystals and the resulting microphysical behaviors of these populations. For temperatures warmer than -40°C, aerosol particles are needed to form cloud hydrometeors. Of these particles, concentrations of ice forming nuclei (IN) are fewer in number than cloud condensation nuclei (CCN). Additionally, the saturation vapor pressure over ice is lower than that over liquid water. These properties together tend to produce cloud liquid water that occurs as a high concentration of small droplets, while cloud ice occurs as relatively few, large crystals.

The implications of these distinct populations on atmospheric radiation are significant; in short, radiative effects are generally dominated by liquid water clouds (e.g., Shupe & Intrieri 2004) that have a much larger total area for a given amount of total mass. The net result is that optically thick clouds, often composed of liquid water, contribute an excess of 40 $W/m^2$ or more of longwave radiation to the surface (Persson et al. 2002; Stramler et al 2011). From a precipitation standpoint, size differences cause ice crystals to fall much faster than liquid droplets and, since Arctic temperatures are typically below freezing, most precipitation is in the solid phase. Further, the imbalance in saturation vapor pressures makes ice grow at the expense of liquid water within a given volume via the Wegener-Bergeron-Findeisen mechanism. In these so-called mixed-phase volumes, riming of liquid droplets onto ice crystals can be a factor. Thus, the interplay of condensed phases within clouds is clearly important for persistence of liquid water and the amount of precipitation produced.

The persistence of stratified layers of supercooled cloud liquid water, in spite of the general tendency for water to freeze, has been one of the primary puzzles of Arctic clouds. Insights into this system have recently emerged, primarily from observations near coastlines, such that Arctic stratiform clouds are understood to persist via a complex web of interactions and feedbacks (e.g., Figure 2.6, Morrison et al. 2012). First, it is becoming clear that supercooled liquid water clouds typically produce ice crystals, usually via liquid-dependent nucleation processes (de Boer et al. 2011). Due to aerosol and nucleation conditions, ice concentrations are limited. The differences in growth rates and particle sizes between liquid and ice hydrometeors are critical; since ice crystals grow much faster than liquid droplets they fall away from the cloud liquid, effectively removing themselves as a sink of liquid water. Additionally, the fact that liquid water layers are optically thick causes them to efficiently cool to space radiatively. This cooling destabilizes the cloud layer leading to buoyancy-driven, turbulent overturning circulations that promote further liquid water growth, in a cloud-sustaining positive feedback.

These cloud radiative and dynamical processes can have an impact on the surface and ABL structure. Cloud-top radiative cooling helps to form temperature inversions and contributes to Arctic low-atmosphere stratification, while cloud-driven turbulent circulations also serve to vertically mix the atmosphere over certain depths (Shupe et al. 2013). Low-clouds often influence surface turbulent heat fluxes (Persson et al. 2002), which also contribute to vertical mixing processes. The relative contributions of in-cloud versus surface forced mixing largely determine whether or not cloud systems are dynamically/thermodynamically coupled to the surface (Shupe et al. 2013). Additionally, vertical mixing related to clouds can support the entrainment of moisture and/or aerosols through the stratified Arctic atmosphere (e.g., Sedlar et al. 2012; Solomon et al. 2011).

These many complex cloud-scale processes that comprise low-level stratiform clouds are thought to be pre-conditioned by the large-scale advective environment (Morrison et al. 2012), where, for example, advection of warm, moist air masses into the central Arctic supports cloud persistence (e.g., Herman & Goody 1976; Curry & Herman 1985). But the balance of remote versus local sources is unclear, particularly over the sea ice. A signature of large-scale moisture advection can be seen in frequent, cloud-top moisture inversions (Sedlar et al. 2012), but the influence of local moisture sources may become more significant under diminished sea ice.

Beyond stratiform clouds, larger-scale frontal clouds, often associated with baroclinic systems, play a significant role in the Arctic hydrologic cycle. Studies have suggested that large-scale synoptic cyclones, and possibly mesoscale polar lows, may be changing in frequency and/or intensity as a result of diminished sea ice extent and other changes (Simmonds & Keay 2009; Inoue et al. 2012; Long & Perrie 2012). These cyclones are thought to be a dominant source of moisture transport into the central Arctic (e.g., Groves & Francis 2002; Sorteberg & Walsh 2008; Jakobson &

Vihma 2010) and thus may have important implications for Arctic regional cloudiness, precipitation, and surface energy budgets (e.g., Cassano et al. 2006). Additionally, the marginal ice zone is known to be an important region for cyclogenesis of storms (Inoue & Hori 2011), with changes in the ice edge likely having implications for regional storm development.

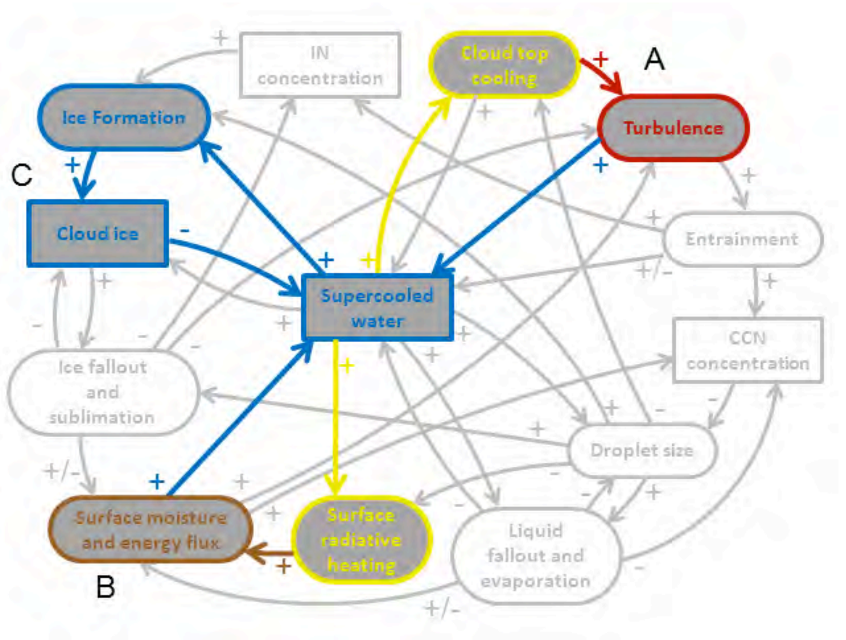


**Fig. 2.6:** Complex web of interactions, links, and feedbacks in Arctic stratiform clouds. Arrows specify direction of influence, while +/- indicate the expected sign of the response. Not all links are shown. After Morrison et al. (2012).

In spite of their potential importance little is understood on Arctic storms and organized cloud systems, including their relative frequency, phase distribution, precipitation formation, mechanisms of cyclogenesis, and interactions with the background state. Moreover, with larger regions of open water and more prevalent first-year ice vulnerable to lead formation, heat and moisture fluxes can introduce complexity in the lower tropospheric structure that can influence these storms. One important result for storms is their influence on the spatial distribution of precipitation. Snowfall on sea ice is increasingly recognized as an important element of the surface energy budget for its role as an insulator and reflector. To understand the spatial distribution of snowfall, requires a process-level understanding of storm organization and related cloud formation.

Underlying the issue of Arctic clouds and precipitation is their interactions with aerosols. Arctic aerosol populations are complex due to marked temporal and vertical variability, and disparate potential origins. Chemical and physical properties dictate their ultimate impacts on radiation and clouds, and these depend on source regions, which can range from locally-produced marine biogenic species to long-range transport of both natural and anthropogenic aerosols and precursors. The relative significance of local sources of cloud-active aerosols within the sea ice pack (Orellana et al. 2011) versus those that are advected over the sea ice from lower latitudes (Shupe et al. 2013) is unknown. Against the relatively clean background state, transient variability occurs as episodic pulses of aerosol are transported into the Arctic with atmospheric synoptic systems (Lundén et al. 2007). Thus, the interplay of large-scale meteorology with the persistent, near-surface Arctic inversion affects the mixing state, aging, vertical structure, and cloud activity of aerosols and their distribution across the Arctic. Land-based observations reveal the broad seasonal cycle of Arctic aerosol (e.g., Quinn et al. 2009), but are representative of an unknown regional domain. Long-term measurements of aerosol over sea ice do not exist. Thus, little is known on how aerosols vary across the Arctic or about the processes that impact their interactions with the climate system, particularly in winter. Enhanced central Arctic observations to characterize the aerosol lifecycle (sources including new particle formation, chemical and physical transformations, and their interactions with clouds) will lead to dramatic increase in knowledge of how aerosols impact the Arctic climate.

To unravel the complexities of central Arctic cloud, aerosol, and precipitation systems requires observational and modeling studies of a similar complexity. Fine-scale processes must be resolved and understood to aggregate and upscale this information in a way that is appropriate for representation in models. Continuous, coordinated, high-resolution observations are needed of cloud presence, vertical distribution, spatial distribution, and microphysical characteristics; of snowfall in the air and reaching the ground; of atmospheric dynamic and thermodynamic structure; of aerosol concentrations and properties that affect clouds; and of surface energy budgets. These observations are needed to characterize the critical local-scale physical process-interactions that determine cloud phase partitioning, atmospheric mixing processes, cloud-aerosol interactions, mechanisms for precipitation over sea ice, and the energetic interactions among cloud, atmosphere, and the sea ice surface. It is also important to determine how representative the operational cloud and atmosphere measurements made at coastal sites and derived from satellites are of these processes over the central Arctic basin.

There are a number of larger-scale linkages that are also important for cloud processes that require broader perspectives that must come from distributed measurements, satellite observations, and modeling studies. The regional context for local cloud conditions can be important such that large-scale advective environment, air mass modification, mesoscale storm structure, and backwards parcel trajectories must be understood. Pan-arctic questions, such as the response of clouds to enhanced basin-wide moisture fluxes or feedbacks with increased open Arctic Ocean water, are largely beyond the grasp of detailed observations and thus must be addressed using model studies. Importantly, for such studies to be effective, model tools must be able to correctly represent cloud and atmosphere physical system interactions in all seasons and in a variety of conditions. Such model advances and evaluations are only possible using comprehensive, process observations such as those proposed for MOSAiC.

## 2.4 How do interfacial exchange rates of biogeochemical process- related trace gases trigger the Arctic climate system?

The coupling of ice and snow physics on one side with the ecosystem on the other side induces numerous biogeochemical reactions during freezing and melting cycles of sea ice which finally results in trace gas exchange with both the overlaying Arctic atmospheric boundary layer (ABL) and the underlying, sea ice influenced, ocean down to the halocline. The year-round process-level observations comprise the complexity needed for tracing those pathways and encompassing feedback mechanisms which impact the ocean-ice-snow-atmosphere system. Pathways to consider are: direct interactions, i.e. from ice, snow or water to the ABL and indirect interactions, where trace gases circulate through more than one environment before reaching the ABL. While the ABL is isolated in terms of dynamics and chemistry from the rest of the troposphere, the halocline restricts the exchange with the deeper ocean, favours microbial degradation processes in surface water and keeps biologically produced trace gases seasonally in surface waters while encouraging gas release during storm events. Quantifying those seasonal-varying fluxes is essential for future improvements of climate models. Understanding the processes behind the observed fluxes of climate-relevant trace gases require a detailed knowledge of both chemistry and dynamics, an intense collaboration and a close link to most of the measurements in atmosphere, snow, sea ice, ocean and ecosystem during MOSAiC.

*Quantifying fluxes: Air-sea gas exchange and radionuclide tracers in ice-affected waters*

Fluxes across the ocean-atmosphere interface in the Arctic are defined by the presence of sea ice. Motions of sea ice produce intermittent connectivity between the ocean and atmosphere when the air-water temperature and biogenic gas ($CO_2$, $O_2$, $N_2O$, $CH_4$) differential can be at its greatest. The Arctic melt season is currently increasing by as much as 10 days/decade (Markus et al. 2009) or ~23% since 1979 (Pabi et al. 2008). Primary production (PP) has followed this trend, increasing by 30% (Arrigo et al. 2008a). The effect of decreasing sea ice cover on the carbon cycle is not clear (Cai et al., 2010), but a larger seasonal oscillation implies an increase in the surface area of the marginal ice zone (MIZ) (Arrigo et al. 2008b). The MIZ represents a unique convergence of biogeochemical conditions that support high rates of PP, and potentially important fluxes of biogenic gases (Delille et al. 2007; Loose & Schlosser, 2011). Upper ocean stratification by meltwater and the presence of ice floes may also modulate the gas transfer velocity (Loose et al. 2014; Rutgers Van Der Loeff et al. 2014) and consequently the flux of biogenic gases. Sea ice production, brine rejection, air-sea gas exchange and primary production in the MIZ have a potentially critical influence on the ocean solubility and biological pumps. To determine how changes in the sea ice cycle affect the solubility pump, a predictive understanding of the role of sea ice in these fluxes and ecosystem processes must be established, starting with a more detailed knowledge of the gas transfer velocity (k). To first approximation, k is often estimated as a function of wind speed (e.g., Wanninkhof, 1992; Takahashi et al. 2009; Bender et al. 2011) Increasing ice cover should reduce wind-driven mixing, and thus k (Stephens & Keeling, 2000; McNeil et al. 2007). However, other processes produce turbulence in the presence of sea ice, therefore the relationship between gas exchange and ice coverage may not be so directly influenced by wind energy (Loose et al. 2016). Experiments indicate that air-sea exchange in the ice zone may be under-estimated by as much as 50% when the wind is less than 10 m $s^{-1}$ (Loose et al. 2016). Even greater uncertainty surrounds air-sea exchange at high wind speeds. Because sea ice acts to entirely mitigate the breaking waves and air bubble entrainment that define open ocean gas exchange at high winds, the exchange mechanisms in the ice zone are likely to be entirely unique. Currently, there is no field study that has attempted to develop a predictive data set for determining changes in gas flux as a function an evolving ice cover. Such a study will require detailed observations of the surface ocean physics - such as the wave field and TKE dissipation (Thomson, 2012). Balancing sea-air fluxes from ocean-based estimates and atmosphere-based estimates may be achievable through comparison of bulk fluxes computed on the atmospheric side (e.g. using covariance flux (Blomquist et al., 2010)) with bulk transfer velocities computed using the $^{222}$Rn to $^{226}$Ra activity ratio method in the surface ocean (Rutgers Van Der Loeff et al. 2014a).

Another consideration of ocean-atmosphere interaction is the aerosol delivery of trace elements to the ecosystem. Aerosol deposition is an important pathway for delivering trace elements, including those of anthropogenic origin, into the Arctic. Assessment of this process has been difficult in the harsh Arctic environment, and limited field studies have forced a reliance on poorly constrained models. The fluxes and fate of atmospherically-derived deposition within the Arctic sea/ice/snow system can be studied using the naturally occurring radioisotope $^{7}$Be. Cosmogenic $^{7}$Be has been shown to be a valuable quantitative tracer for atmospheric deposition of trace elements (Kadko, 2000; Cámara-Mor et al. 2011; Kadko et al. 2016). While it is clear that $^{7}$Be can indicate recent atmosphere-ocean exchange, wintertime deposition rates of cosmogenic nuclides from the central Arctic are sparse at best, and a study of $^{7}$Be as part of MOSAiC can greatly improve our knowledge of trace element deposition in polar winter and its subsequent redistribution into sea ice and the surface ocean.

### *Reactive chemistry in the coupled ocean-ice-snow-atmosphere system*

Unique chemistry in the Polar Regions converts chemically inert halide ions present in the Arctic Ocean, ice, snow, and aerosols are converted into reactive halogen species (e.g. Br2, Br atoms, and BrO) that modify atmospheric chemistry in the ABL. During Arctic spring reactive halogen species in the ABL have the potential to deplete ozone (an important atmospheric oxidant and greenhouse gas) to near zero levels as well as to oxidize both elemental mercury and dimethyl sulphide. In addition, the release of chlorine via heterogeneous chemistry in Arctic and continental atmospheric chemistry has been suggested as important for atmospheric oxidation, ozone formation, and radical cycling (e.g. Liao et al. 2014). Despite significant research progress (detailed e.g. in the reviews of Simpson et al. 2007; Abbatt et al. 2012; Simpson et al. 2015), major questions still remain as to how, when, where and why halogens are released from snow, ice, and aerosols and how they impact the Arctic environment (see e.g.

Jacobi et al. 2010; Simpson et al. 2007; Pratt et al. 2013, Thomas et al. 2011; Thomas et al. 2012; Toyota et al. 2011; Toyota et al. 2014a; Yang et al. 2008; Yang et al. 2010). In addition, there is very limited information on halogens in the central Arctic boundary layer during the winter/spring transition, when this chemistry is most active. The impacts of halogen chemistry can be far reaching, including modification of the lifetime of methane as well as modification of the oxidation processes that determine background Arctic aerosol concentrations.

### *Mercury*

Halogens oxidize elemental mercury leading to drastic atmospheric mercury depletion events (AMDEs) (e.g. Ariya et al., 2004). Despite numerous studies (see Simpson et al. 2007, 2015; Abbatt et al. 2012), the regional sources and mechanisms for halogen activation remain under discussion (e.g. Toyota et al. 2011; Yang et al., 2010; Pratt et al. 2013; Thomas et al. 2012a), with large uncertainties in the central Arctic Ocean. This unique biogeochemistry that occurs at the Arctic Ocean surface on ice/snow must be understood in order to predict how future reductions in sea ice will modify the chemical processes that feature heavily the ABL.

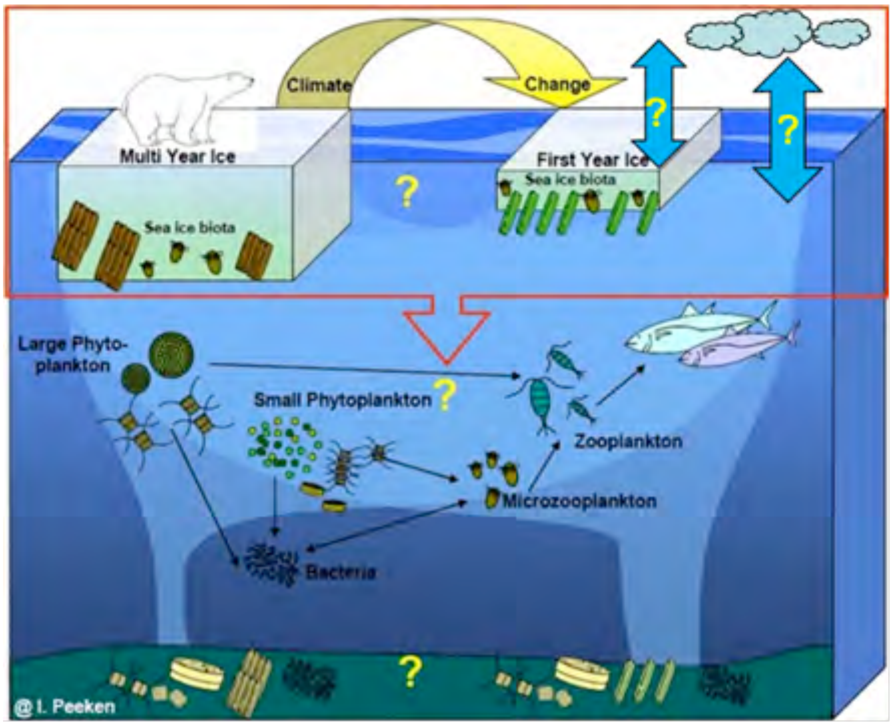


**Fig. 2.7**: The shift from MYI to FYI and resulting unknown processes for biogeochemical cycles.

Mercury is a global contaminant that can cause adverse health effects to wildlife and humans (Lamborg et al. 2014). The majority of mercury originates from human activities in the mid-latitudes and is transported over long distances to the Arctic, though the exact pathways and timing remain under debate (Sonke & Heimbürger, 2012). During AMDEs the otherwise unreactive elemental mercury is converted into oxidized forms (Gaseous oxidized mercury-GOM and particulate oxidized mercury-POM) that due to their high reactivity, readily deposit to snow, sea ice, and open waters (see e.g. Ariya et al. 2015; Toyota et al. 2014b). The deposited reactive mercury is likely preferentially transformed into its toxic methylmercury forms (monomethyl- and dimethylmercury), which then biomagnifiy along the arctic trophic chain, reaching ultimately harmful levels in top predators (Heimbürger et al. 2015). Large uncertainties arise from our incomplete understanding of oxidation pathways, deposition, and reemission (Angot et al. in press; Soerensen et al. 2016). Due to its sensitivity, mercury species measurements will also advance our understanding of other trace gas fluxes in the arctic ABL.

*Aerosol production and the Sulphur cycle*

Upon sea ice melt, the climate-active gas dimethyl sulphide (DMS) is released from the huge pool of DMSP, present in sea ice organisms. After emission to the atmosphere, the oxidation of DMS affects atmospheric chemistry, potentially promoting the formation of new aerosol particles and cloud condensation nuclei (CCN) in remote marine regions. This can increase the reflectivity of skies and clouds, resulting in a cooling of Earth's climate. Although a potential climate feedback role for DMS as postulated by Charlson et al. (1987) is subject of debate (Quinn & Bates 2012; Cameron-Smith et al. 2011), sea ice melt zones are without doubt the areas with highest DMS concentrations (Lana et al. 2011) and sea ice itself is hypothesised to play a key role in this. Concentrations of both DMS and DMSP are three orders of magnitude higher in ice than in surface waters (Tison et al. 2010; Stefels et al. 2012). Data on the direct coupling between sea ice, surface ocean and atmosphere is, however, still limited. Consequently, the impact of a changing sea ice extent is uncertain.

Although DMSP and DMS concentrations in sea ice (Levasseur et al. 1994; Delille et al. 2007; Tison et al. 2010), and DMS emission from sea ice to the atmosphere (Zemmelink et al. 2008; Nomura et al. 2012) have been measured, the measurements are limited to spring and summer ice and no study has attempted to identify the microbial community responsible for DMS production. Similarly, other biogenic aerosol sources in sea ice have been targeted for detailed study. Leck & Bigg (2005) identified similar particles (EPS, salt, diatom frustules) in the sea surface microlayer of leads and the lower boundary layer. In addition, the unique environmental stresses of sea ice, including high salinity, high UV light, and high oxygen stress suggest a physiological stress response in ice algae and bacteria that may include aerosol production, including DMS (Hefu & Kirst 1997).

Low molecular weight products produced by the reaction of algal derived HIO with DOC are another example of stress-induced aerosol nucleators that may be significant in sea ice (Hill & Manley 2009). Although there is no explicit relationship to aerosol production, ice algae are additionally known to produce organohalides, including bromoform (Sturges et al. 1992).

*Greenhouse gases*

Measurable fluxes of trace gases have been observed between the ice and atmosphere indicating that ice may act as a source (and possibly sink). The net effect of these sources and sinks is not clear and significant uncertainty is associated with the magnitude of fluxes. Sea ice surface conditions, including snow cover, superimposed ice formation and surface flooding, also affect the rate of gas flux (Nomura et al. 2013).

Atmospheric methane concentrations in the high Arctic are the highest on earth. Periods of low variability and large short-time variability observed in recent years focus the view on unknown and as yet not detected sources and sinks in the interior Arctic. Sea ice is highlighted to be either a potential source of bacterial produced methane or may act as a buffer for terrestrial fossil methane from degrading permafrost regions. Recent studies have identified previously un-quantified sources of atmospheric methane to the Arctic, such as sub-sea permafrost degradation (Portnov et al. 2014; Portnov et al. 2013), methane bubbling and fossil methane seepage along thaw features (Walter et al. 2012; Walter et al. 2008), all of which could be linked to the increasing Arctic temperatures. Sea ice itself is also implicated in the role of transferring methane to the atmosphere from the oceans (Damm et al. 2015). A cascade of feedback processes triggered by melting and freezing events may induce seasonally the release of methane from remote sources in the interior Arctic. To understand this cascade and to quantify the fluxes a complete measurement of methane fluxes at all interface is a needed. Through a combination of continuous measurement and triggered spot sampling, isotopes of carbon and hydrogen in elevated samples of methane can be very instructive in determining the source of the methane (e.g. O'Shea, 2014), thus helping to both constrain the sources of methane to the Arctic, and determining isotopic signatures for sea ice related methane emissions.

Increase of nitrous oxide ($N_2O$) concentration in the atmosphere contributes significantly to climate change and may affect natural systems related to snow, ice and frozen ground (including permafrost) (IPCC, 2007). $N_2O$ is a potent GHG naturally present in the atmosphereIt has a lifetime of 114 years and a global warming potential (GWP) of 298 (Forster et al. 2007) 300 time greater than that of $CO_2$. $N_2O$ is also described as the dominant ozone-depleting substance emitted in the 21st Century (Ravishankara et al. 2009). However, there are still large uncertainties and gaps in the understanding of the cycle of this compound through the ocean, particularly in sea ice. Sources and sinks of $N_2O$ are poorly quantified. The main processes (with the exception of transport) cycling $N_2O$ within the aquatic environment are nitrification and denitrification. Only one study (Randall et al. 2012) presents $N_2O$ measurements in sea ice. They conclude that sea ice formation and melt has the potential to generate sea-air or air-sea fluxes of $N_2O$, respectively. Studies on ammonium oxidation and anaerobic bacterial cultures show that $N_2O$ production can occur in sea ice (Priscu et al. 1990). Denitrification can act as a sink or a source of $N_2O$. Randall, et al. (2012) ascribed low levels of $N_2O$ measured in the bottom of the sea ice to bacterial denitrification. Recent observations of significant nitrification in Antarctic sea ice (Fripiat et al. 2014) shed a new light on nitrogen cycling within sea ice. It has been suggested that nitrification supplies up to 70% of nitrate assimilated within Antarctic spring sea ice. Corollary, production of $N_2O$, a by-product of nitrification, can potentially be significant. Hence, a deeper understanding of processes is needed to understand $N_2O$ sources and emissions in Polar Regions.

### *Volatile organic carbons (VOCs)*

A significant fraction of naturally oceanic VOCs (compounds playing a significant role in tropospheric ozone and organic aerosol budgets) are produced in the oceanic upper layers by direct or indirect phytoplankton activity processes. Among these VOCs, isoprene is produced under the action of photosynthetic active radiation on phytoplankton metabolism (Bonsang et al. 1992; Shaw et al. 2003; Bonsang et al. 2010); carbon monoxide or mono-unsaturated hydrocarbons (ethene, propene, butenes) are derived from indirect processes involving, principally, the photodegradation of CDOM under the action of UV radiations (Kettle 2005; Riemer 2000) and, for a minor part the plankton metabolism (carbon monoxide) (Gros et al. 2009). Recent studies in the Arctic Ocean (Tran et al.; 2013; Boissard et al. 2016) confirmed the existence of these production processes. However, an important issue remains on the role of the sea ice as a potential source of VOCs whose intensity and seasonal variability remains to be investigated. Indeed, sea ice can act as a reservoir of organic matter (Scully and Miller 2000) and simultaneously can prevent sea air gases exchanges. Investigations in Arctic sea ice cores (SIC) by Xie et al. (2005) and Song et al. (2011) and more recently by Boissard et al. (2016), suggested that sea ice could be an important source of VOCs and carbon monoxide probably derived from the degradation of organic matter, and/or enriched CDOM. VOCs in SIC showed a huge variability, with strong vertical gradients and a probable link between SIC age and VOCs amount (Boissard et al., (2016). These recent findings need further investigations, in particular in terms of seasonal variations and VOCs oxygenated fraction.

### *In- sea ice photochemistry*

Photochemistry likely has a large role to play in biogeochemical cycling in sea ice, but studies of in-ice photochemistry are lacking (Miller et al. 2015). Organic carbon concentrations in sea ice are high due to selective incorporation during growth (Müller et al. 2013) and biological activity within sea ice brine pockets. Photochemical oxidation of organic carbon in sea ice may therefore play a significant role in polar carbon cycling (Xie & Gosselin, 2005). Photochemical breakdown of organic carbon in sea ice has been traced using carbon monoxide (Xie & Gosselin, 2005; Song et al 2011), and inferred using known sea ice irradiances and organic carbon concentrations (Belzile et al. 2000). King et al. (2005) and France et al. (2011) identify sea ice brines as potentially oxidizing media due to the photochemical breakdown of hydrogen peroxide and nitrate. The oxidizing capacity of sea ice will party determine the fate of oil in an increasingly industrialised Arctic, and changes in sea ice oxidizing capacity with season are not known. Targeted measurements of relevant photochemical species provide an opportunity for first order gains in knowledge and would require core sampling / in-situ sampling of potentially important species such as $NO_3^-$, $NO_2^-$, $H_2O_2$, CDOM, DOM. There is a close link to optical measurements planned in the sea ice team.

*Biogeochemical modelling*

MOSAiC is ideally suited to be complimented by sea ice biogeochemical model experiments since it covers simultaneous measurements of a large variety of biogeochemical variables, which are or need to be constrained in models. Vancoppenolle and Tedesco (2015) indicate various applications for the modelling of sea ice biogeochemical processes including the understanding of processes that are difficult to observe, the closing of the budget of chemical elements, and the upscaling of the results of local observations. They further highlight the need to evaluate ice algae models with more observations, including all aspects of the system (algae, organic matter, nutrients, light and brine), in terms of stocks and concentrations, to increase the scope of models towards relevant processes, to understand the salient features of the elemental cycles in sea ice, and to simplify models for their implementation in Earth System Models.

0-D/1-D models focusing on process studies are designed to develop parameterisations, and require a quantitative understanding of the processes in question, in addition to a conceptual framework. These models require site-specific variables, rates and the variations both over time from field and from laboratory experiments, preferably with multiple replicates to constrain uncertainty ranges (Steiner et al. 2015). Steiner et al. 2015 provide guidance to help modellers and observers improving the integration of measurements and modelling efforts and advance toward the common goal of understanding biogeochemical processes in sea ice and their current and future impacts on environmental systems. A variety of 1-D models, which have been developed and refined in recent years (Jodwalis et al. 2000; Jin et al. 2008; Tedesco et al. 2010; Tedesco and Vichi; 2014, Moreau et al. 2014, 2015; Vancoppenolle et al. in prep.; Lavoie et al. 2005, Mortenson et al. Submitted; Hayashida et al. in prep., Mortenson et al. in prep.) will be applied to the MOSAiC field experiment in order to support the understanding of the processes observed during MOSAiC, to refine and further develop parameterisations of as of yet disregarded sea ice biogeochemical processes and try to identify processes which should be included in large scale models. All existing 1-D models represent somehow the essential components of the microbial cycle in sea ice (Vancoppenolle & Tedesco, 2015), while some models already include first attempts at representing carbon (Tedesco et al. 2012; Moreau et al. 2015; Mortenson et al. in prep.), dimethylsulfide (Jodwalis et al. 2000; Hayashida et al. under review) and other gases (Moreau et al. 2014) in sea ice. The inherent dependence of sea ice algae on light has already stimulated discussion of model applications of light transfer through snow and sea ice (Vancoppenolle & Tedesco, 2015; Light et al. 2015; Abraham et al. 2015) and will be discussed and developed further based on the focused measurements during MOSAiC. From a modelling point of view, a major strength of the MOSAiC plan will be the provision of observations of physical and biogeochemical properties: 1) on a daily to weekly basis, which is an ideal timescale for accurate model validation; ii) for an entire year, including the less sampled seasons such as autumn and winter, which often remained unevaluated; iii) in a remote region of the Arctic where very little information on biogeochemical and ecosystem processes is available; iv) in a comprehensive manner, meaning that all of the relevant properties will be observed and sampled at the same time, providing an holistic view of the ecosystem state and element cycling. For example, the role of sea ice as mediator for DMS and DMSP, the contribution of bacteria to the pool of remineralization in the sea ice environment, the potential grazing role of heterotrophs, the coupling between the sea ice, pelagic and benthic ecosystems, are all processed poorly known and currently mostly left out from models. The MOSAiC plan will thus allow the implementation of these and other previously poorly constrained processes into state-of-the-art biogeochemical models. The results of the 1-D parameterisation developments will be transferred to large-scale and possibly Earth system models to allow insights into potential climate change impacts on sea ice biogeochemical cycles and related feedbacks to ocean and atmosphere.

*Carbonate system/$CO_2$*

The inorganic carbon system (or carbonate chemistry) in sea ice and seawater is controlled by several processes (e.g. Fransson et al. 2013; Delille et al. 2014). For example, by biological activity (photosynthesis/respiration), precipitation/dissolution of particulate inorganic carbon (e.g. ikaite) and gas exchange process ($CO_2$ release/invasion) with ocean and atmosphere. The magnitude of each contribution to the carbonate/$CO_2$ system is, generally, examined by the measurements of the total dissolved inorganic carbon (DIC) and total alkalinity (TA) and by the comparison on the DIC/TA diagram (e.g. Zeebe & Wolf-Gladrow, 2001). However, conclusive results of the net effect of these processes is precluded because the process of sea ice formation/decay varies during the year yet measurements of this type over a continuous annual cycle in pack ice are scarce.

Assuming that none of the processes shown above (biological activity, precipitation of ikaite and gas exchange) is active driving the carbonate chemistry during sea ice formation, the relative increase of DIC and TA in brine will be equal to that of brine salinity. This would lead to significantly high DIC and TA and consequently high partial pressure of $CO_2$ ($pCO_2$). By measuring two variables describing the carbonate system (DIC, TA or pH), we can calculate $pCO_2$ in the brine/seawater/bulk ice during sea ice formation. The $CO_2$ solubility in water is known at temperatures above 0°C and for salinity up to 45 (Weiss 1974; DOE 1994; Millero 1995). Given that brine temperature is below freezing and salinity higher than seawater salinity, we usually assume that this function could be used for the $CO_2$ solubility in brine. However, Brown et al. (2014) indicated that measured and calculated values of the carbonate/$CO_2$ system parameters in brine can differ by as much as 40%. Direct measurement of $pCO_2$ within sea ice and brine were examined previously by using in situ silicone gas exchange chambers (“peepers”) (Miller et al. 2011) and a membrane contractor equilibrator with pumping the brine from the sackhole (Delille et al. 2014). For example, “peepers” are not suitable at the low temperatures due to the fact that gas diffusion rates in silicone decrease and peepers require long equilibration times (Miller et al. 2015). Therefore, during MOSAiC campaign, we will be examining development of new methods to evaluate the carbonate system within brine, in addition to the processes within the sea ice throughout the formation/decay of the sea ice.

Due to the recent rapid increase of the atmospheric $CO_2$ concentration, the amount of $CO_2$ uptake by the ocean has increased, resulting in the so-called ocean acidification (OA). This invasion of the $CO_2$ to the ocean modifies the carbonate system within the seawater, resulting in a decrease in ocean pH and carbonate ion concentration. In the Arctic Ocean, increased freshwater supply from sea ice melting, river runoff and glacial water discharge containing low salinity and usually high content of organic matter have shown to decrease pH and provide a positive feedback on OA (e.g. Fransson et al. 2013). In sea ice, as indicated above, $pCO_2$ changed drastically, indicating that algae community was exposed by high $CO_2$ concentration (Coad et al. 2016). Therefore, we will examine the impact of the high $CO_2$ (OA) to the marine and ice algal communities throughout the season during the MOSAiC campaign.

### 2.5 How do sea ice and pelagic ecosystems respond to changes in Arctic sea ice?

High-latitude ecosystems that use sea ice as a substrate, habitat and foraging ground are characterized by strong spatial heterogeneity and pronounced seasonal dynamics that reflect their physico-chemical environment. The coupled interactions between sea ice, biology, and chemistry of the ocean-atmosphere system are, however, generally understudied. A lack of measurements covering entire annual cycles limits our ability to predict pan-Arctic integrated productivity and responses in key ecological processes. MOSAiC offers the unique opportunity to study biogeochemistry and ecology in the framework of those processes thought to exert strong controls on Arctic biota and related carbon and nutrient cycles. Critical processes to consider will include sea ice formation, lead dynamics, melt pond formation, ocean mixed layer dynamics, and wind-induced upwelling of nutrients. Improved understanding of the biologically-mediated fluxes of elements and energy between ocean, sea ice, and atmosphere also requires the investigation of underlying ecosystem dynamics in the context of these processes, at temporal and spatial scales not previously resolved.

*Ecosystem processes across coupled atmosphere-sea ice-ocean systems*

With MOSAiC, a more complete understanding of the fluxes of important elements (C, N, O, P, S) between the atmosphere, ice, and ocean systems can be gained through a broad focus on ecosystem processes in the ice and the water column as well as the linkages between these systems. The emphasis will be on quantifying and linking important processes, i.e. PP, but also microbial respiration and nutrient remineralization, sympagic meiofauna growth and grazing, and pelagic processes, such as meiofauna growth, and grazing and pelagic processes, such as mesozooplankton feeding, growth and reproduction. Standing stock measurements of major biological and chemical components are needed to obtain integrated estimates for energy, elemental, and compound specific budgets. In addition, rates of grazing and nutrient recycling will be critical in supporting deeper understanding of ecosystem responses.

While great advances have been made in understanding how sea ice biota persists in harsh conditions, the factors that lead to biomass patchiness, including local nutrient and light supply, and thus PP heterogeneity, are all poorly understood in terms of their spatial variability and seasonality. Moreover, observations of how microbial, algal, and metazoan community structures and functions interact and control these processes are further limited. Changes in the magnitude and timing of Arctic food sources are likely to alter the development and seasonal succession of higher trophic levels (Søreide et al. 2010, Wassmann & Reigstad 2011). Some understanding of the central Arctic sympagic and oceanic ecosystems has been obtained through research cruises (primarily focused on spring-summer-fall season; e.g., Arctic Ocean Section 2004) and drifting ice camps (e.g., T-3, AIDJEX, SHEBA, Tara, TRANSSIZ, N-ICE). Few biological measurements have been made using autonomous sensors in the Central Arctic due to limited sensor capabilities. Bio-optical sensors have only recently been integrated into Ice-Tethered Profilers (ITPs), but have already revealed contrasting onsets of blooms in the Beaufort Gyre compared to the European basin (Laney et al. 2013). Considerable work has been done on continental shelves and Arctic marginal seas (e.g., SBI, Carbonbridge, CASES, CFL, N-ICE, Svalbard and Greenland fjords), which are systems that share some characteristics with the Central Arctic (e.g. trophic linkages) but have fundamentally different drivers of PP. These expeditions have provided seasonal standing stocks of prominent taxa (e.g. key genera of phytoplankton, ice algae, mesozooplankton), which are intricately tied to seasonal cycles in irradiance, snow thickness on sea ice, and sea ice draft and extent, and limited work on trophic linkages (e.g., rate processes such as grazing, production) of phytoplankton and zooplankton. Bacterial and microzooplankton abundance and production, the underlying processes driving the dynamics at each trophic level, the fluxes of material between ecosystem components and between the pelagic and sympagic realms, and seasonality in these processes remain less understood. The vulnerability and resilience to change of the ecosystem and key players in the cycling of organic matter, nutrient transformations, and energy transfer are largely unknown (e.g. AMAP 2013). For example, it has been hypothesized that a change in the timing of sea ice retreat could have important impacts on secondary producers such as large copepods with life histories that are evolved to exploit a previously predictable food supply (Match-Mismatch Hypothesis; Søreide et al. 2010). It has also been suggested that the dominant large copepod species (*Calanus hyperboreus*) in the Central Arctic may not be endemic and must be sustained through input from bordering shelf and slope systems (e.g., Olli et al. 2007; Ji et al. 2012). Unknowns such as these limit our ability to describe and predict trophic linkages, ecosystem functions, and how organism-specific phenologies will respond to a changing physical and chemical environment.

The seasonality of production cycles will be an additional focus. It is currently unknown if the lengthening melt season will significantly increase Arctic Ocean productivity; however, the timing of seasonal production cycles and length of the growth season will likely be altered (Søreide et al. 2010). Many mesozooplankton species have life cycles timed to ice and water column PP cycles. For example, the copepod *Calanus hyperboreus* synchronizes its reproduction so the first feeding stages of its offspring take advantage of the ice algal bloom (Falk-Petersen et al. 2009). Other species may use ice algal or phytoplankton blooms to directly fuel their reproduction while some have mixed strategies (Daase et al. 2013; Søreide et al. 2010). Many species use lipids accumulated during the short growing season to sustain them in a resting state during the long, dark winter period when food is much more limited. Still others remain relatively active, although presumably at much reduced metabolic rates (Berge et al. 2015). It is likely that alterations to the timing of PP cycles and growth season length have detrimental effects on higher trophic level production and energy flow pathways that in turn could have impacts on ecosystem biodiversity and productivity.

Longer growing seasons, higher temperatures as well as altered nutrient and light regimes could also set the stage for invasion of the central Arctic by subarctic populations of endemic as well as new expatriate species, a phenomenon termed 'atlantification' in the European sector of the Arctic (Hegseth and Sundfjord 2008; Rat'kova and Wassmann 2002). The increasing occurrence of coccolithophore blooms in the Barents Sea (Smyth et al. 2004) or their higher contribution in sediment traps in the Fram strait (Bauerfeind et al. 2009; Lalande et al. 2013; Soltwedel et al. 2015) can already be taken as an indicator of this trend. The aforementioned changes in the Arctic appear to also favor small species such as *Micromonas*, which, for example, increase in abundance in the Canada Basin (Li et al. 2009). Such picophytoplankton may have competitive advantages in low-nutrient/high-recycling situations, probably due to their higher surface:volume ratio, their ability to thrive as mixotrophs (McKie-Krisberg and Sanders 2014) and potentially nitrogen fixation, as recently suggested for some Arctic prokaryotes (Blais et al. 2012). A regime shift, e.g. from diatom-dominated assemblages to picophytoplankton, would have far-reaching implications for Arctic ecosystems and carbon export.

### *Controls on primary production in sea ice and pelagic ecosystems*

Arctic ecosystems are undergoing drastic environmental changes, as the melt season is increasingly prolonged by up to 10 days per decade (Markus et al. 2009), but with very high regional variability. The long-term effects of this decrease in sea ice on organic and inorganic carbon cycles are not clear (Cai et al. 2010), even though a larger oscillation between winter maximum and summer minimum ice cover implies an increase in the marginal ice zone (MIZ) area (Arrigo et al. 2008b). The MIZ region represents a unique convergence of biogeochemical conditions that periodically support high rates of primary production (PP), and potentially drive important fluxes of organic matter and nutrients (Delille et al. 2007; Loose & Schlosser 2011, Barber et al. 2015). A change in MIZ area, i.e. ~30% increase (Arrigo et al. 2008a) is likely to result in profound changes in PP across the high Arctic. Recent remote sensing studies show an increase of pelagic phytoplankton PP by up to 20% due to increased light caused by more open water in both space and time (Arrigo et al. 2008a; Pabi et al. 2008; Arrigo and van Dijken 2011). Additionally, high phytoplankton biomass accumulations have occurred under thinning sea ice suggesting overall enhanced productivity in the future Arctic (Arrigo et al. 2012).

Due to low solar insolation angles, light is a key factor driving PP in ice-covered oceans (Leu et al. 2015). Light penetration in the Arctic is reduced by sea ice as well as snow cover (Mundy et al. 2005). In the framework of climate warming, the Arctic atmospheric moisture budget is expected to drive increasing snow cover (Callaghan et al. 2011; Cohen et al. 2012) and thus to reduce light availability for PP. In contrast, the trend towards first year ice (FYI) will substantially increase short-wave transmission through ice (Nicolaus et al. 2012), although the system is more sensitive to snow cover than ice thickness. Ultraviolet light transmission is particularly sensitive to changes in snow and ice thickness and is expected to increase (Fountoulakis et al. 2014). In the MIZ, phytoplankton likely experience higher mean irradiances owing to a shallower upper mixed layer in response to sea ice melt and warming. However, in this scenario, phytoplankton are also more suspectible to high-light stress, which can set into motion a cascade of physiological responses resulting in reduced photosynthetic capacity and increased oxidative stress.

Disadvantageous physiological responses to excess light could be further exacerbated in low pH and/or nutrient limited conditions (Gao et al. 2012, Hoppe et al. 2015).

The magnitude and timing of sea ice and pelagic PP are further constrained by both small- and large-scale changes in nutrient availability (Gradinger 1999; 2009). Tremblay et al. (see review 2015) identified the importance of measuring nutrient fluxes and their control on the magnitude of PP in the Arctic Ocean. Current nutrient enhancements may be a relatively short-term phenomenon that will recede unless there are additional supplies of nutrients to the surface ocean (Walsh et al. 2005). Several processes that could result in enhanced PP via alterations to nutrient fluxes include, but are not limited to increased storminess and resultant mixing of nutrients from below the nutricline into the euphotic zone (Ardyna et al. 2014), increased photochemical production of ammonium, due to increased light exposure, and increased delivery of DOM by rivers (Xie et al. 2012). Additionally, freshening of surface waters due to sea ice melt, river run off, and changes in wind driven circulation will also have consequences for pelagic PP (Yamamoto-Kawai et al. 2009; Timmermans et al. 2011). Nishino et al. (2011) see the Eurasian basin as a region where the biological pump could be more efficient due to the increase of nutrients by uplifted isohaline surfaces caused by the transpolar drift. Furthermore, sea ice melt can produce a more transparent surface layer, increasing UV exposure, and promoting PP at greater depth (Granskog et al. 2015). However, shallower mixed layers resulting from stratification due to sea ice melt could also result in earlier nutrient depletion in the euphotic zone (Hill et al. 2013).

Increased snowfall and cover could also alter current PP by wet deposition of allochthonous compounds (e.g. NOx) onto sea ice. Increased snow cover can result in submersion of the ice surface below sea level, which may introduce a new Arctic sea ice habitat, the so-called infiltration layer, which is ubiquitous in the Antarctic sea ice zone and highly productive (Haas et al. 2011; Kattner et al. 2004). Not unlike pelagic PP, ice algal PP will likely be altered by changes in these environmental conditions. Ice algal PP is low compared to large ice edge phytoplankton blooms (Sakshaug 2004). But despite their moderate production, ice algae are potentially the only food source for pelagic fauna such as young copepods early in the year, thereby fuelling higher trophic levels in the Arctic (Søreide et al. 2010). Decreased ice cover and increased light exposure may increase absorption of solar heat by algae, resulting not only in earlier growth but also melt-out of ice algae.

Thus, receding sea ice has a strong influence on sea ice and pelagic PP in the Arctic Ocean (Sakshaug 2004; Perrette et al. 2011). A better understanding of the processes regulating light availability, nutrient supply, and the biological processes controlling organic matter and nutrient fluxes are urgently required to determine if the presently observed PP enhancement is short-lived or will persist. Wassmann & Reigstad (2011) present three conceptual models describing how biogeochemical cycling in the seasonal ice zone could be affected by climate change. They present evidence that suggests there is currently little certainty on whether the Central Arctic will become more or less productive. The complexity of such predictions is due in part to the compounded effects of increased light availability, possibly more frequent storms, enhanced river discharge, and melting permafrost. These factors could act to alter Arctic PP through direct and indirect mechanisms as soruces of episodic nutrient input, drivers of stronger stratification with the potential to dampen nutrient supply, and through the differential responses of ice algae and phytoplankton. Improved understanding of these mechanisms will further inform us on how Arctic ecosystems will respond to predicted climate variations.

### *Sea ice and pelagic communities*

Populations of ice algae living in sea ice are incorporated into new ice during freeze up (Niemi et al. 2011) as a result of scavenging by frazil ice (Garrison et al. 1983; Riedel et al. 2007) and via the circulation of seawater through consolidated ice (Weissenberger & Grossmann 1998). Sea ice is also seeded with a large number of microorganisms such as bacteria and archaea. High-biomass Arctic sea ice, can contain more than $10^{10}$ bacteria $L^{-1}$ (Maranger et al.

1994), and hundreds of micrograms of chlorophyll *a* $L^{-1}$ (Gradinger et al. 2009, Juhl et al. 2011). Together, these microbial communities are subject to a variety of temporal and spatial dynamics, which can result in huge ranges in biomass, productivity, and nutrient and organic matter fluxes. Sharp gradients in sea ice physical and chemical parameters shape the heterogeneous distribution of sea ice microbial communities, but identification of the interactions between these organisms and their sea ice environment remain limited. Recently, Bowman (2015) synthesized measurements of sea ice microbial community structure, bacterial production, and primary production to elucidate the role microbes play in sea ice carbon cycling, and found both mutualistic and antagonistic interactions among the microbial community. Increased attention to microbial interactions and genomic capacities beyond carbon cycling are further needed to understand how sea ice and pelagic microbial communities and the processes they control will respond to decreases in the persistence of Arctic sea ice. Leveraging advances in meta-genomics/transcriptomics/proteomics will be key to exponentially increasing our capacity for understanding both sea ice and pelagic algal and microbial community composition and function over the annual cycle, especially the under-sampled winter season. Additionally, sympagic meiofauna diversity and biomass are important in structuring sea ice communities. Their life cycles are physically linked to sea ice, and their functional role as grazers is key to elucidating how sympagic meiofauna may control fluxes through sea ice. For many sympagic meiofauna, measurements of standing stocks and observations of these ecosystem level processes are limited to seasonal studies.

### *Resolving episodic and seasonal biological and ecological phenomena*

MOSAiC is a unique opportunity to observe and measure specific processes and rates at biogeochemically- and ecologically-relevant temporal scales. In addition to the intensified frequency at which we plan to conduct observations and measure biological, chemical, and ecological rate processes, MOSAiC provides the opportunity to resolve natural phenomena, both episodic and seasonal, through integrative systems-based approaches. The periods between seasons, or transitions, have been identified as key periods for increased sampling intensity and strategic experimental work to measure rates and rate proxies. For example, springtime sea ice melt can result in large under-ice algal blooms (Arrigo et al. 2012, Galindo et al. 2016). Algal cells released from melting sea ice into the water column (Juul-Pedersen et al. 2008), may initiate under-ice algal blooms (Lizotte, 2001). These blooms contribute significantly to biogeochemical fluxes. Carbon fixation by microalgae and subsequent transport into the ocean's interior contributes to sequestration of $CO_2$. Moreover, these carbon fluxes feed pelagic (Juul-Pedersen et al. 2008) and benthic ecosystems (Ambrose et al. 2005). These blooms have also been found to produce high levels of DMSP, followed by enlarged DMS fluxes into the atmosphere, which potentially has impacts on atmosphere-sea ice-ocean feedbacks (Galindo et al. 2016). However, many questions remain about the nature, fate, and function of the seeding material. Likewise, there is little known about biological and chemical processes during the Arctic polar night. However, recent work has shown unexpected biological activity by several trophic levels previously thought to have significantly reduced activity during Arctic winter (Berge et al. 2015). Interactions across trophic levels and diversity were elevated in some habitats during winter (Berge et al. 2015), which suggests that previous disregard for the role Arctic polar night may play in biological and ecosyetm-wide processes is no longer acceptable. Coorindated efforts across MOSAiC themes will aim to measure biological and ecological responses to epsiodic and seasonal physicochemical changes in the atmosphere, sea ice, and ocean of the high Arctic during the winter season to further elucidate how processes during this period impact observations through the annual cycle.

### *Dissolved Organic Carbon in sea ice*

Part of the difficulty in constraining $CO_2$ fluxes from ice stems from the fact that, in addition to inorganic carbon, ice can also contain organic carbon compounds, which may be respired to produce additional $CO_2$. [Considering DIC alone cannot assess this additional source of carbon to the inorganic carbon pool. Carbon flux measurements are further complicated by differences in release processes and physical exchange processes in sea ice (refer to section

2.4.1)]. Dissolved organic carbon (DOC) in sea ice is variable and patchy (Thomas et al. 2001). As with salt, DOC in sea ice is trapped in the ice microstructure; the average DOC concentration in brine pockets may be higher than in seawater (Melnikov 1997), especially where ice algae are present. Laboratory and field evidence shows that disaggregated DOC is conserved in a similar manner to salt in sea ice brine as the freezing process takes place (Giannelli et al. 2001), although some fraction of the DOC pool may be retained in the ice in excess relative to salts and contribute to an abiotic excess of DOC in sea ice already at initial ice formation.

Sea ice formation can incorporate both psychrophilic bacteria and algae into the ice microstructure. These organisms protect themselves from freezing and osmotic shock by secreting a polysaccharide gel known as EPS (Krembs et al. 2002). EPS can represent a significant portion of the DOC found in Arctic sea ice (Rauschenberg et al. 2010; Thomas & Dieckmann 2010) both in summer and winter (Krembs & Engel 2001; Krembs et al. 2002). At lower temperatures, sea ice microbes secrete more EPS, yielding an inverse relationship between temperature and DOC concentration bound up in EPS. As ice warms in spring and irradiances increase, ice algae multiply and may continue to secrete a large fraction of their carbon uptake as a physiological response to the abrupt salinity changes resulting from ice melt (Krembs et al. 2002). In addition, EPS in sea ice appears to be a locus for heterotrophic microbial colonies, thereby possibly enhancing respiration and thus increasing $CO_2$ concentrations. Much of the patchiness in sea ice DOC is thought to occur because psychrophilic bacteria and ice algae coalesce and multiply on EPS mats (Krembs et al. 2002; Meiners et al. 2008). While there is large variability on the average DOC content in sea ice, microbes in sea ice are capable of accessing and converting it to inorganic carbon, even at sub-freezing temperatures. Coordinated measurements of DOC remineralization, bacterial and algal production, microbial and algal community diversity and function will provide new mechanistic insights into sea ice DOC dynamics.

#### *Particulate Organic Carbon (POC) export from the seasonal ice zone*

Although ice algal PP is a smaller $CO_2$ sink in the Arctic Ocean than in the Southern Ocean, it can nonetheless account for a significant fraction of $CO_2$ uptake in ice-covered Arctic regions (Mikkelsen et al. 2008). Organic carbon that is not remineralized by sea ice bacteria is exported to the water column at a rate determined by its composition (Juhl et al. 2011) and the dynamics of melt (Lalande et al. 2015). On the continental shelf, sea ice-derived POC supports the growth of a rich and diverse benthos community (McMahon et al. 2006). Over the deep Arctic basins, sea ice derived POC can be sequestered below the mixed layer. Numerous factors, most of which are poorly constrained, determine the rate of PP and decay, as well as the fate of sea ice derived organic material. These factors include the abundance and renewal of nutrients (being affected by transport, vertical mixing, and *in-situ* regeneration), the availability of light, the size, composition, and density of sea ice derived POC, the rate of bacterial production and respiration in sea ice and water column, and as well as the grazing rates of micro-, meso-, and macro-zooplankton at the ice-water interface and in the water column.

Boetius et al. (2013) reported mass export of the POC through aggregates of the ice alga *Melosira arctica* to the deep sea floor in large areas of the Eurasian basin during the record Arctic sea ice minimum in 2012 (Parkinson & Comiso 2013). This species was originally mainly associated with MYI but new observations demonstrated their massive development under FYI as well. *M. arctica* is known for its high content of dissolved and particulate DMSP (Levasseur 2013), but it is currently unknown which conditions were responsible for this massive biomass accumulation. For sea ice biota, it remains to be seen if such events will continue and what the fate of DMSP packed aggregates will be (Levasseur 2013). Understanding these events will require added focus on measuring precursors and DMS concentrations to improve current models of the sulfur-ice cycle (Elliott et al. 2012).

*Summary*

Most Arctic marine biogeochemistry and ecosystem studies have focused on early spring and summer and on shelf-slope regions, with limited examination of rate processes, trophic linkages, their implications to biogeochemical cycles, and their role in the central Arctic ecosystem. Some understanding has been gained from past overwintering studies in the Central Arctic and along the Arctic margins. The only winter study to address biological processes across the entire ecosystem was the Circumpolar Flaw Lead study, which gave insights from bacteria to beluga whales (Deming and Fortier 2011) and revolutionized previous concepts of Arctic winter biology, but focused on the Amundsen Gulf rather than the Central Arctic. Arctic biogeochemical systems are dynamic and participate in complex interactions with sea ice, snow, atmosphere, and ocean. Thus, it is crucial to improve our understanding of biogeochemical and ecological processes operating within the coupled Arctic system from sea ice freeze up, over winter, into the spring bloom, and throughout the summer, focusing on the Central Arctic where most pronounced changes are expected (Wassmann & Reigstad 2010). MOSAiC is designed to address these basic needs to better define ecosystem trophic linkages and phenologies, and to improve ecosystem models and prediction capacities for future climate change scenarios.

*Progress in sea ice ecosystem models*

Deal et al. (2011) was one of the first to produce a model for Arctic sea ice that is capable of simulating lateral and temporal variations in PP and biomass. This model has demonstrated that the extent and duration of sea ice cover are the most important processes regulating annual PP in the high Arctic. Further model exercises have shown that ice growth is necessary to provide ice algae with sufficient nutrients to maintain their colonies, and that high nutrient concentrations in surface water are associated with high PP in sea ice. These simulations, however, are hampered by a lack of basic parameterizations and inputs on ice carbon uptake rates, initial biomass concentrations, and winter seawater nutrient concentrations (Deal et al. 2011). In regions where previous studies have been conducted model results agree well with estimates from various case studies. Currently, there are several coupled and/or integrated Arctic models with ecosystem parameterizations for PP, biomass, sea ice, and nutrients aimed at improving estimates of Arctic primary productivity (Zhang et al., 2010; Popova et al., 2012; Hill et al., 2013; Vancoppenolle et al. 2013; Jin et al. 2012, 2015).

Using a coupled physical-biological model to simulate future Arctic ecosystem scenarios, Slagstad et al. (2011) found that the Eurasian shelves will become more productive, while productivity in the Barents Sea will decrease. This is caused by a mismatch between the primary producers and higher trophic levels (Wassmann et al. 2011). To understand these processes, and make future predictions, ecosystem models must be coupled with realistic ocean physics models. Of particular importance is vertical mixing, which is essential to understand the supply of nutrients into the euphotic zone during winter (Popova et al. 2010). Actual nutrient measurements are limited and winter values can be variable depending on the water mass history (Tremblay & Gagnon 2009). As a result of these challenges, PP estimates based on assumed nutrient levels are biased and inhibit accurate modelling of future PP changes (Popova et al. 2012). Physical, chemical, and biological processes interact in distinctive and complex ways, which yet need to be understood in full detail. Thus, an understanding of the rapidly changing polar environment and its impact on PP requires interdisciplinary measurements in the understudied Central Arctic. Just recently, Steiner et al. (2016) published a call to the community on what information modellers need to enable improved and more accurate numerical sea ice-biogeochemical models, which provides an important future context for the work outlined here.

### 2.6 How do ongoing changes in the Arctic climate system impact large-scale heat, momentum and mass fluxes and how do these changes feed back into the Arctic climate and ecosystem?

Atmospheric and oceanic transport of heat from lower latitudes to the Arctic is a key driver of the Arctic climate system; in annual means, lateral heat transport exceeds the downward solar radiation. In mass transport, the essential components include the southward ocean transport of freshwater and the northward atmospheric transport of moisture, clouds, and aerosols. In both media, the transports consist of contributions of the mean circulation and disturbances, synoptic-scale cyclones being most important for the latter. In addition, rivers that discharge into the Arctic Ocean transport freshwater and particles.

During this century, the large-scale Arctic circulation has changed from a zonally dominated circulation type, which can be well characterized by the Arctic Oscillation (AO), to a more meridional pattern, the Arctic Dipole (AD), where a high-pressure center is typically located in the Canadian Arctic and a low in the Russian Arctic (Overland & Wang 2010). This pattern favors advection of warm, moist air masses from the Pacific sector to the central Arctic, and has likely contributed to sea ice decline (Graversen et al. 2011). Through increased release of ocean heat to the atmosphere during autumn, sea ice decline has, in turn, directly contributed to a modification of large-scale atmospheric circulation, favoring the Arctic Dipole (Overland & Wang 2010).

The AO and AD closely interact with synoptic-scale cyclones, which are responsible for the majority of heat and freshwater transport to the Arctic. Cyclone activity is most vigorous in the Greenland Sea during all seasons, except summer, when the Norwegian, Barents and Kara Seas have a comparable amount of activity (Sorteberg & Walsh 2008). The number of cyclones travelling into the Arctic is similar in all seasons, but in winter cyclones are more intense and shorter lived than in summer. Moisture transport variability is mainly driven by variability in cyclone activity over the Greenland and East Siberian Seas (Sorteberg & Walsh 2008). Transient cyclones contribute 80-90% of the total meridional moisture flux (Jakobson & Vihma 2010). The main moisture flux into the Arctic occurs in the Norwegian Sea and Bering Strait sectors with the main moisture export via the Canadian sector. Considerable uncertainty remains in the vertical distribution of moisture transport. According to radiosonde data, the meridional moisture flux across 70°N peaks at approximately 850 hPa (Overland & Turet 1994; Serreze et al. 1995), whereas according to ERA-40 reanalysis the median peak level in winter is at 930 hPa and in other seasons at 970–990 hPa (Jakobson & Vihma 2010).

Several studies have addressed recent changes in synoptic-scale cyclones in the sub-Arctic and Arctic. A statistically significant increasing trend in the frequency of cyclones entering the Arctic during recent decades has been detected (Zhang et al. 2004; Sorteberg & Walsh 2008; Sepp & Jaagus 2011), although the frequency of cyclones formed within the Arctic basin has not increased (Sepp & Jaagus 2011). Zhang et al. (2004) also report an increase in the intensity of cyclones entering the Arctic from mid-latitudes, suggesting a shift of storm tracks into the Arctic, particularly in summer. They also found that Arctic cyclone activity displays significant low-frequency variability, with a negative phase in the 1960s and a positive phase in the 1990s. A problem with these analyses is that it is difficult to fully distinguish between true and apparent changes in cyclone occurrence and properties. Apparent changes may originate from changes in the amount, type, and quality of observations assimilated into reanalyses. Above all, the number of high-latitude radiosonde stations has decreased while the amount of satellite data has strongly increased. In spite of these changes, there appears to be a prevailing consensus on an increase in Arctic cyclone activity. This change is potentially related to sea ice decline. For example, in the case of Polar lows, Kolstad & Bracegirdle (2008) and Zahn & von Storch (2010) have associated an observed northward migration with the retreating sea ice margin. The atmospheric response to sea ice extent, however, strongly depends on the mean state of the atmosphere (Balmaseda et al. 2010).

Stroeve et al. (2011) detected an autumn increase in cyclone-associated precipitation over the 2000-2010 period. According to Zhang et al. (2013), the net atmospheric moisture transport to the Arctic has increased by 2.6% per decade, in line with a 1.8% per decade increase in Eurasian Arctic river discharge. This increase has accelerated in the last decade and a record high discharge occurred in 2007 (Shiklomanov & Lammers 2009). The increasing trend has been attributed to warming effects, including intensifying precipitation minus evaporation, thawing permafrost, increasing greenness, and reduced plant transpiration, but the causal physical processes remain unclear (Zhang et al 2013).

The strong decline in autumn sea ice over the last decades has intensified interest in the interactions between sea ice conditions and the atmosphere (c.f., Budikova 2009). The decline in Arctic summer sea ice is connected with atmospheric circulation responses in following months (e.g., Overland & Wang 2010; Liu et al. 2012; Francis & Vavrus 2012; Screen et al. 2013) and could be linked with anomalous cold European and Asian winters (Honda et al. 2009; Petoukhov & Semenov 2010; Cohen et al. 2012; Jaiser et al. 2012). Francis et al. (2009) suggested that ice conditions during summer/autumn can impact northern hemisphere large-scale atmospheric features the following winter by modifying lower tropospheric stability, cloud variability, and poleward thickness gradient, and thus implicitly the characteristics of the polar jet stream. Honda et al. (2009) showed that Arctic sea ice conditions in fall can impact winter climate over Eurasia. Using model simulations, they found that low sea ice conditions during fall are associated with cooler, low-level temperatures in the following winter over Eurasia.

Jaiser et al. (2012) describe possible pathways for how autumn sea ice anomalies impact the atmospheric flow patterns on short to intra-seasonal timescales. They show that negative summer sea ice anomalies trigger increased heat and moisture fluxes from the Arctic Ocean that contribute to decreased vertical atmospheric static stability and increased lower-tropospheric moisture in autumn. These amplify baroclinic wave energy fluxes and thereby influence the large-scale atmospheric circulation patterns, leading to cold winter temperatures in Eurasia and other effects.

Since most previous studies are based on observations of limited duration, and often restricted to large anomalies only, the reported results are often not conclusive or robust enough for further statistical analysis. Hopsch et al. (2012) analyzed two different time periods (satellite era with a strong trend in sea ice concentration, and a longer period including pre-satellite data with a negligible trend), to allow for a more statistically significant assessment of obtained signals. Their estimated circulation changes suggested feedbacks between the time-mean flow, quasi-stationary planetary waves, and baroclinic waves in response to sea ice changes. Jaiser et al. (2013) analyzed the stratospheric response to the observed Arctic sea ice retreat using the European Centre for Medium Range Weather Forecast Re-Analysis (ERA-Interim) atmospheric data from 1979-2012. They showed how changes in September sea ice concentration impact tropospheric and stratospheric geopotential heights the following winter. During low ice phases a negative tropospheric AO pattern is found, which is connected to a weakened stratospheric polar vortex and warmer stratospheric temperatures. Furthermore the analysis revealed enhanced upward Eliassen-Palm (EP) fluxes due to planetary waves for low ice conditions. Strong stratospheric anomalies in the Atlantic/European region are associated with a weaker polar vortex. Low ice periods are connected with additional tropospheric wave energy excitation in the Pacific/North America region and influence the stratosphere through three-dimensional planetary wave propagation, which complicates the interaction between tropical and polar regions.

Some degree of regularity in the large-scale atmospheric response to sea ice decline may indicate potential for seasonal predictability of weather conditions, at least for autumn and early winter seasons. However, more work is needed to better understand how Arctic ABL processes regulate surface-induced modification of synoptic and large-scale circulation. The challenging issues include deepening of the ABL and weakening of the temperature inversion (Francis et al. 2009; Deser et al. 2010), interaction of convection and baroclinic effects (Petoukhov & Semenov 2010), and the difference in the cross-isobaric angle between sea ice and open ocean (Petoukhov & Semenov 2010).

Since current large-scale models include major errors in representing the ABL (Tjernström et al. 2005; Jakobson et al. 2012) and other influential processes, the above-mentioned challenges demonstrate the need for enhanced observational and modelling activities in the Central Arctic, such as those proposed for MOSAiC. It will be critical to link these detailed, Central Arctic activities with regular observations at circum-Arctic observatories that are well positioned to capture large-scale fluxes into and out of the Arctic. Measurements made as part of the International Arctic Systems for Observing the Atmosphere (IASOA) network are particularly important. This type of large-scale coordination allows for more advanced studies on large-scale transports and air mass modification over the Arctic Ocean. Moreover, these activities provide a critical link between intensive MOSAiC activities in the sea ice with international programs interested in sub-seasonal, seasonal, and decadal Arctic predictability and the broader connections between Arctic processes and global weather and climate patterns.

## 3. EXPERIMENTAL APPROACH

One of the overarching goals of MOSAiC is to improve model representations, predictions, and forecasts of central Arctic processes and sea ice. To make appreciable progress towards this goal requires detailed, interdisciplinary understanding of, and observational constraints on, the coupled physical, biological, and chemical processes at play in the central Arctic Basin. The MOSAiC experimental approach is designed to provide the observations that are needed to address identified model needs, deficiencies, and priorities, and to ultimately serve as a testbed for model improvement.

At their core, the observational activities of MOSAiC will embody a comprehensive, interdisciplinary and sustained *process study*. A central organizational element is the state of the sea ice, as it plays the role of integrator in the system by adjusting and responding to fluxes and forcings. In particular, the *sea ice life cycle* is important here, extending from initial freezing, through first year growth, deformation, and transport, towards melt, decay, and export. To facilitate this perspective, a *sea ice Lagrangian* approach will be taken, where observational facilities will drift with the evolving sea ice. Observations will be specifically designed to characterize exchange processes in the system, particularly at the top and bottom interfaces of the sea ice. These processes that couple the atmosphere, ice, and ocean participate in numerous feedbacks, can be sensitive to systemic change, have strong seasonal dependence, and represent some of the greatest difficulties for models. One tenant of MOSAiC is that these interdependent processes must be examined simultaneously because of the importance of coupling, feedbacks, and seasonality in the system. **The scope of observing activities is thus based on those aspects of the central Arctic climate system that participate in climate-relevant feedbacks and interactions with other elements of the system.** A singular focus on any individual element of this system will fail to provide the comprehensive process-level understanding that is needed.

To obtain the multi-scale, coupled-system observations required for MOSAiC, a multi-tiered observational approach (Figure 3.1) will be implemented that includes: 1) a central observatory for characterizing detailed processes; 2) distributed regional networks for characterizing spatial variability and heterogeneity; and 3) coordinated activities for linkages to large-scale phenomena. The observations made at each of these scales will provide important context and detail for those made at other scales. Many of the associated measurements will be conducted operationally for the duration of the MOSAiC field phase, while there will also be episodic intensive observing periods that focus on individual processes or seasonally-specific aspects of the system. Each of these primary observational approaches will be described in this section, including the measurements that will be made, a first-order prioritization of measurements, estimates on the readiness and feasibility of the proposed measurements, and the specific science questions and objectives that the measurements will help to address. In many cases the core observations will be based on mature technologies; however, MOSAiC will also be a platform for targeted technology advancement and development that will support future measurements of the Arctic climate system.

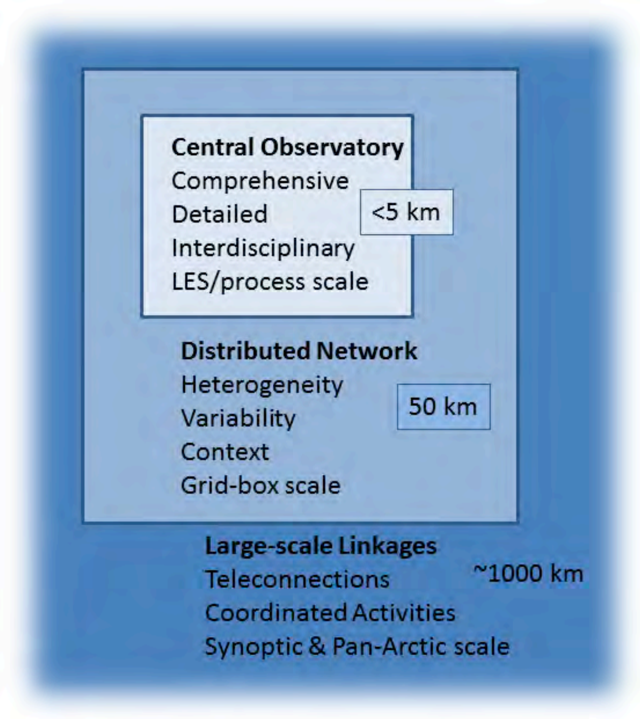


**Fig. 3.1:** A multi-tiered observational approach.

### 3.1 Central Observatory

The MOSAiC Central Observatory will be designed to intensively characterize processes in the local "column" extending from the atmosphere through the sea ice and into the ocean using suites of state-of-the-science instruments (Figure 3.2). A research icebreaker will serve as the central platform for operations and the headquarters for field activities. Deployed aboard this ship will be as much research equipment as feasible and operationally realistic. On the ice directly adjacent to the ship (within 1 km) will be a "camp" for scientific measurements that require direct access to the sea ice and/or spatial separation from ship infrastructure. This camp will be established as early within the drift as possible and thereafter routinely accessed by research personnel. Local-scale observations may also be distributed over a somewhat wider range (<5 km) for measurements needed to characterize local heterogeneity. Depending on seasonal conditions, remote sites within this domain will have routine, but not daily, access by research personnel. Together measurements from this local domain (0-5km) are expected to resolve local-scale processes, to provide detailed context for spatially distributed measurements (see Section 3.2), and to be used in coordination with single-column, large-eddy-simulation, and process modeling activities.

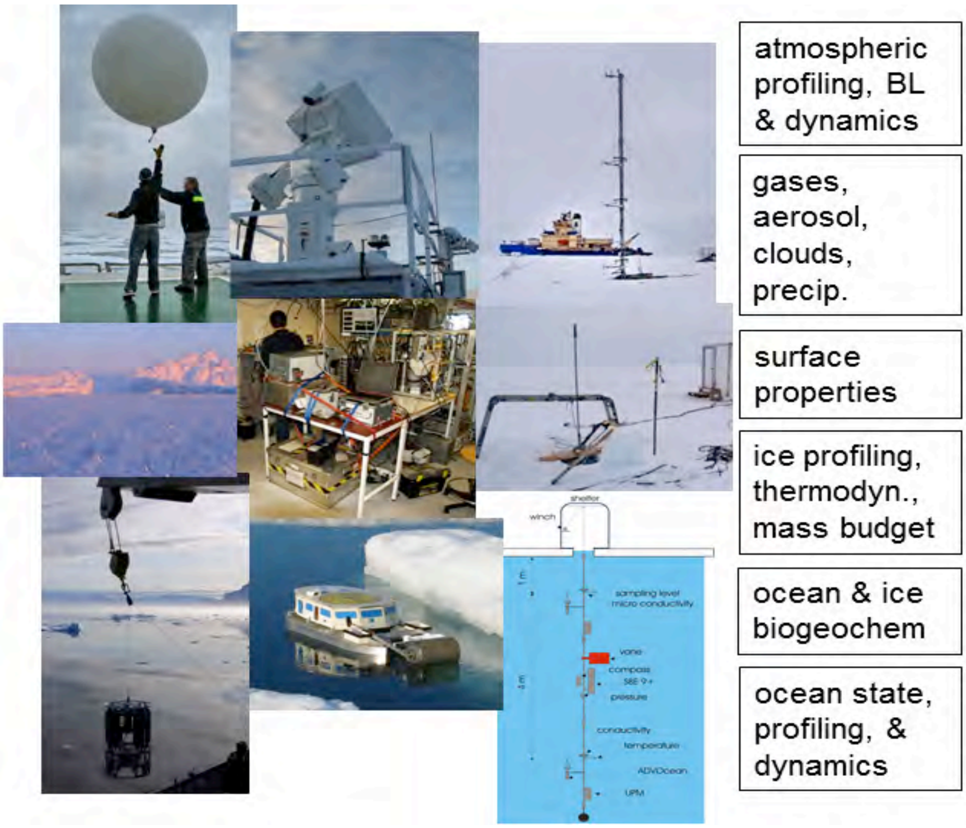


**Fig. 3.2:** General overview of measurements at the MOSAiC Central Observatory.

Based on prior experiences at SHEBA, the Russian drifting stations, and other projects, it is clear that a ship is highly justified and necessary for the central base of operations. A ship enhances safety for on-site personnel in an environment that contains thin ice, extreme weather, and polar bears. Such a stable platform is needed to operate many of the sophisticated atmospheric and laboratory instruments that cannot be operated from the sea ice itself and allows for operations in open ocean and thin sea ice conditions that may not support an ice camp for a full year. Overall, the ship will facilitate logistics, allow on-site personnel to focus on obtaining high quality observations, and promote more stable and consistent measurements.

While the central observatory is intentionally designed to promote inter-disciplinary process research, descriptions of the specific measurements and instrument suites required to address the high-level MOSAiC science questions will be handled in distinct sections focused on the atmosphere, sea ice, ocean, and biological/biogeochemical systems.

### 3.1.1 Atmosphere system

Atmospheric measurements at the Central Observatory will be designed to provide a physical understanding of local-scale, vertical column interactions. Detailed measurements will aim to characterize clouds, the atmospheric boundary layer, the surface layer, and surface energy fluxes. These will address the specific objectives of understanding lower tropospheric processes that directly impact energy interactions with the surface. At higher altitudes, measurements will be made to characterize the mid- and upper troposphere to understand the environment in which lower tropospheric processes manifest, and to provide the upper-level and larger-scale forcing for these processes. Finally, aerosol and chemistry measurements are needed to understand particle sources, their direct and indirect radiative effects on the surface, and their impacts on key atmospheric structures such as clouds.

To provide critical context for most MOSAiC atmospheric analyses, it is necessary to characterize the large-scale and upper-level atmospheric kinematic and thermodynamic structure. Routine radiosonde observations at 6-12 hour timescales will be a backbone of this characterization, offering high accuracy profiles of temperature, moisture, and winds. A radar wind profiler is needed to derive sub-hourly vertical profiles of wind speed and direction to capture the evolution in mesoscale dynamics.

Finer detail is required for understanding smaller scale processes that occur in the ABL. Thus, at low levels it is critical to include high-temporal and high-spatial resolution profiles of both kinematic and thermodynamic parameters. These profiles can be obtained with a suite of ship-based, remote sensors combined with in situ profiles from routine radiosondes and periodic tethered-balloon soundings. In particular, for thermodynamic parameters, building off the baseline radiosonde observations, temperature and humidity profiles will be derived for the lowest ~2 km of the atmosphere from ground-based microwave and infrared radiometers and/or Raman lidar. These will offer higher-resolution information on atmospheric stability and help track variability on sub-hourly timescales.

The ABL kinematic structure will be described using a combination of radar wind profiler, sodar, Doppler lidar, and cloud radar. The first two of these together provide good spatial coverage of the ABL in most conditions, and their region of overlap (200-500 m) is the typical height of low-level jets, which have dynamical importance for vertical mixing and turbulence. These measurements will help link jets to larger-scale structure and variability. Doppler lidar and cloud radar measurements provide high-resolution measurements, both within and below clouds, which are useful for resolving sub-mesoscale vertical motions and turbulence parameters that are critical for describing cloud and atmospheric mixing processes. The high temporal resolution ABL measurements are important to document the occurrence and impacts of small mesoscale variability. Moreover, the combination of high-resolution low level kinematic and thermodynamic information can offer insight into dynamical parameters that are of importance for understanding ABL processes (e.g., Richardson number).

Clouds play important roles in radiative, dynamical, and precipitation processes. Clouds will be observed over the full tropospheric depth above the Central Observatory using a suite of complementary, ground-based remote sensors including millimeter-wavelength radars and depolarization lidars. These will be paired with multi-channel microwave and infrared radiometers to characterize a host of properties including cloud presence, boundaries, phase, liquid and ice water contents, and mean particle size at high temporal resolution (<1 min). All of these detailed properties are needed to understand the complex interactions of clouds with atmosphere and surface. The spatial organization of cloud systems around the Central Observatory will be observed using a centimeter-wavelength, scanning radar with the ability to map spatial variability of these systems over scales of multiple 10s of km.

Quantitative precipitation estimates are important for understanding daily-to-annual evolution of snow cover, and surface energy and mass budgets of sea ice. Precipitation rates can be estimated from both shorter- and longer-wavelength radars. Scanning precipitation radar measurements have the advantage of mapping spatial variability of precipitation over a 50+km radius and can be used to understand the dynamical air motions and mesoscale atmospheric structure influencing the precipitation volume. Precipitation mass will be measured using multiple snowfall gauges to constrain the total mass reaching the surface and provide a dataset to evaluate remote-sensing precipitation measurements.

Little information exists on aerosols over the central Arctic, especially in winter, and thus significant questions remain about aerosol sources, composition, and interactions with clouds. Comprehensive measurements will be made to characterize aerosol properties on a continuous basis in the near-surface environment, including size distributions, composition, hygroscopicity, cloud condensation nucleus concentration, ice nucleus concentration, black carbon concentration, and optical properties. Gas-phase tracers and chemical markers at the surface will provide information on the extent of mixing of long-range transported air masses to the surface. These measurements will be made near the surface via an inlet and ship-based laboratories. Profiles of aerosol properties are highly desirable for understanding aerosol-cloud interactions and potential sources of aerosols. Unfortunately, it is difficult to make such measurements on a routine basis and it is best to make them using in situ aerial platforms. If feasible, tethered-balloon, UAS, and/or helicopter profiles of aerosol concentration over the lowest 1 km above the Central Observatory will provide very important information on vertical distribution of aerosols relative to the lower atmosphere structure (see Section 3.2).

It is important to characterize the structure, spatio-temporal variability, and processes of the atmospheric surface layer and surface itself. When sufficient ice is present, a multi-level tower instrumented with sonic anemometers, fast hygrometers, fast gas analyzers, and meteorological measurements will describe the turbulent fluxes of momentum, sensible heat, moisture, $CO_2$, and $CH_4$ between the lower atmosphere and surface. Additionally, a full suite of down/upwelling, direct/diffuse, longwave/shortwave broadband radiative flux and some spectral, narrow band radiative flux measurements will be made along with conductive heat flux through snow and ice. Multiple suites of these surface energy budget measurements will be made to characterize different ice types within the local Central Observatory domain. A major challenge will be to sustain these surface flux measurements over the full sea ice life cycle, in particular early in the freeze up season to capture the transition from open ocean to very thin sea ice. This may have to be accomplished using other platforms, such as UAS. Additionally, profiles of atmospheric radiation will be important to understand radiative flux divergence through the atmosphere. Such measurements will likely require UAS or helicopter flights, or coordination with manned aircraft missions (see Section 3.2).

### 3.1.2 Physical sea ice system

The Central Observatory is a key element in the sea ice observation strategy. There are five goals associated with the sea ice observational effort at the Central Observatory site.

1. Characterize the properties of snow and ice cover and understand the processes that govern these properties.
2. Determine the mass and fresh water balances.
3. Determine the partitioning of solar radiation in ice.
4. Describe the spatial variability and temporal evolution of the snow and ice cover.
5. Integrate sea ice measurements with other components.

To achieve these goals a coordinated, integrated, interdisciplinary approach is needed. Different ice types will be sampled over the course of a full annual cycle to determine the spatial variability and temporal evolution of the ice cover. Work at the Central Observatory will entail four types of snow and ice observations: physical properties, morphology, optical properties, and mass balance. Three different measurement approaches will be used to make these measurements including selected sites, autonomous stations, and surveys.

On a small scale, snow and ice physical properties will be characterized using snow pits and ice cores. Snow pits will be used to determine vertical profiles of snow temperature, density, stratigraphy, and grain size. Ice cores will be taken and processed generating vertical profiles of ice temperature, salinity, density, brine volume, particulates, and crystallography. Oxygen isotope ratios will be determined from snow and ice samples to estimate the amount of superimposed ice and snow-ice present. These properties are all important for understanding evolution of the ice pack, its conductive and transmissive properties, its thermodynamics, and its interactions with biogeochemical processes.

Snow and ice morphology on the Central Observatory floe will be examined. Measurements of both surface and bottom topography will provide a three-dimensional description of the surface and underside of ice. The spatial distribution of snow depth and ice thickness will be measured. Morphological properties of pressure ridges, such as length, width, depth, and block size, will be measured manually. Through a combination of walking surveys and airborne observations using helicopter or UAS the spatial distribution and temporal evolution of melt ponds will be tracked throughout the melt season, specifically targeting pond area, depth, number density, and connectivity.

At selected sites representing the available ice types near the Central Observatory, operational time series measurements will be made of apparent and inherent optical properties using Surface Radiation Buoys. These will include spectral measurement from 350 to 2500 nm, total solar radiation integrated over wavelength, and the Photosynthetically Available Radiation. Spectral albedos and transmittances will be routinely measured both at selected sites and along surveys lines every 2-4 days. The spectral irradiance field within the ice cover will be measured through boreholes at least once a week. Measurements of apparent optical properties (albedo, transmittance) will be combined with ice physical property observations and radiative transfer models to determine the inherent optical properties (absorption coefficient, scattering coefficient, phase function) of basic ice types including snow, the surface scattering layer, drained ice, and interior ice. These measurements will be coordinated with those in the atmosphere and ocean to characterize the flow of radiative energy through the sea ice system, which impacts ice thermodynamics, upper ocean heat content, and ice/ocean productivity.

The mass balance of ice near the Central Observatory will be a critical property to determine and track over time, as it serves to integrate fluxes from atmosphere and ocean. Snow accumulation/melt and ice growth/melt will be measured at multiple sites using ablation stakes and thickness gauges. All four modes of ice melt will be measured: surface, bottom, internal, and lateral. Surface and bottom melting will be determined by tracking the position of the surface and bottom over time. Internal melt and freezing will be determined from a time series of vertical temperature profiles measured using thermistor strings through the snow and ice. Mass balance sites will be installed along the edge of the floe to measure lateral melting. Retreat of the ice edge and the changing wall profile of the edge due to melting will be measured. Ice growth and melt will be interpreted within the context of nearby measurements of atmospheric and oceanic forcing terms. Additionally, coordinated measurements of atmospheric processes leading to snowfall will provide important context for surface accumulation.

Three different approaches will be used to acquire a complete time series of snow and ice properties. Several measurement sites will be selected to include all available ice types and conditions (e.g., undeformed, deformed, first year, multiyear, bare, ponded, floe edge). These sites will be visited routinely (daily to weekly) during the entire drift experiment. During those visits measurements will be made of surface conditions, physical properties (snow pits, ice cores) mass balance (snow depth, ice thickness, ice growth, surface melt, and bottom melt), and optical properties (spectral albedo, in-ice irradiance, and transmittance). Implications of these for biological and biogeochemical processes are discussed in Section 3.1.4.

Complementing the multiple selected sites will be a few semi-autonomous stations. Some of these autonomous stations will be collocated with other elements within the local measurement domain (atmosphere, ocean, and ecosystem). The autonomous stations will measure ice mass balance and spectral incident, reflected, and transmitted radiation. The stations will also have web cameras. Data at these stations will be automatically recorded and transmitted via satellite. Additional autonomous stations will be part of the MOSAiC Distributed Network.

Both the selected sites and autonomous stations provide point measurements of the properties and processes of ice cover. To investigate spatial variability within the local Central Observatory domain, these point measurements will be supplemented with surveys. Snow depth, ice thickness, pond depth, and spectral albedo will be measured along survey lines that are hundreds of meters in length, using instruments (e.g., electromagnetic ice thickness device, spectroradiometer, cameras) installed on sledges or carried. Using Lidar the surface topography will be mapped over areas of hundreds of meters on a side. Underwater remotely operated vehicles will be used to measure spectral transmission and under ice topography along transects. Changes in surface conditions will be monitored using cameras mounted on the ship and meteorological towers. Photo-mosaics of ice around the Central Observatory will be routinely made using cameras mounted on lightweight UAS.

### 3.1.3 Physical ocean system

Upper ocean processes affect sea ice growth and melt by supplying heat (e.g., absorption and redistribution of solar radiation and vertical transport of heat stored in deeper water masses) and, in the presence of open water, through surface waves deforming and fracturing the sea ice. The upper ocean is also a region of increasingly important biological activity, which acts to fix, and potentially export, atmospheric $CO_2$ and can attenuate the absorption of solar radiation. Water column measurements will thus focus on understanding the processes that govern:

1. Delivery of oceanic heat to the ice-ocean interface.
2. Absorption of solar radiation and the fate of the resulting heat.
3. Deep ocean context and vertical contributions.
4. Production and export from the euphotic zone.

Three-dimensional momentum, heat and freshwater budgets provide fundamental building blocks for addressing these objectives. The dominant contributions to these processes vary over space and time, are influenced by lateral and vertical advection, and are different within distinct vertical layers of the ocean. Since the fate of sea ice is one of the primary drivers of MOSAiC, upper ocean processes are a leading priority. Deeper ocean processes can also be important via their impacts on the upper ocean, yet require a different scale of observations.

To provide large-scale context for ocean processes that impact sea ice, routine profiling of velocity, temperature, salinity, and dissolved oxygen is needed from the surface or sea ice bottom down through at least the top several hundred meters of ocean. This profiling will help to map water column thermal, kinematic, and density structure to identify important water masses, estimate currents, and quantify vertical fluxes of energy. For example, such profiling will help to characterize the vertical location and heat content of Atlantic Water relative to the rest of the ocean column. Since the deeper ocean evolves more slowly, deeper profiling will be on approximately a daily basis.

The ocean mixed-layer evolves much more quickly and is the important interface that dynamically and thermodynamically links the ocean to sea ice. It is often a few 10s of meters thick, shoaling in the summer, and at certain times and locations it can be shallower than 10m (Toole et al. 2010). Due to solar penetration, this layer is important for biogeochemical processes. Because of these considerations, and to characterize ice-ocean coupling processes, the upper ocean requires high temporal and vertical resolution measurements from the halocline, through the mixed layer, and up to the surface or sea ice. To identify and observe all of these layers year round will require routine measurements down to approximately 50-100m.

Turbulence and vertical mixing are important at many levels within the ocean system. Diapycnal mixing at the base of the mixed-layer (and/or euphotic zone) drives vertical fluxes of heat, freshwater and nutrients that may contribute significantly to mixed layer budgets. Processes that drive mixing include wind forcing, either direct or modulated by overlying ice cover, convection due to surface cooling and/or brine rejection and shear instabilities driven by internal waves. Direct, high resolution measurements of turbulence throughout the upper ocean will be used to quantify mixing rates associated with these rapidly-evolving, small-scale dynamical processes. Further, observations that can resolve internal waves and convective overturning, along with measurements of wind stress and ice motion, are needed to understand the underlying mechanisms.

Near-surface mixing is particularly important for sea ice. Continuous eddy-covariance measurements of turbulent fluxes just below the ocean-ice interface are critical for understanding ice-ocean friction velocities, vertical heat fluxes, mass diffusion, and other processes. Ideally such measurements are made at 2-3 locations near the Central Observatory to characterize local-scale variability and provide redundancy for these important measurements. Frequent microstructure profiling of velocity, temperature, and salinity within and just below the mixed layer is needed to track the evolving mixed layer structure and heat content as it relates to fluxes into and out of this layer. High resolution measurements are needed year round, and particularly during key periods such as fall freeze up when upper ocean heat is released.

Solar transmission and optical properties of ocean water are important factors controlling the net solar input into the mixed layer and its vertical distribution. These in turn impact upper ocean heat storage and biology. The integrated light field in the upper ocean depends on incoming solar radiation, water clarity, water optical properties, and upper ocean stratification. Vertical profiles of downwelling spectral irradiance will provide a basis for understanding the processes that affect light availability, while measurements of beam attenuation will quantify clarity and inherent optical properties. These measurements will be obtained under sunlit conditions multiple times per day to characterize the diurnal cycle and the dependence of these profiles on other properties of the upper ocean, overlying sea ice, and snow.

### 3.1.4 Biology and biogeochemical system

Two principal advantages to the MOSAiC observatory are the capacity to occupy an inertial "ice" region and to do so for an extended period of a year. Because the Central Observatory will drift with the ice the potential exists to conduct time-integrated measurements that focus on the ice as the inertial control volume. Both the ocean and atmosphere will flow past the inertial ice region (IIR). Observations of physical, biological, and biogeochemical transformations and succession inside the ice should focus on monitoring the ice column while making flux measurements at both the ice-water and ice-air interfaces. Importantly, these measurements will be made over a complete and continuous annual cycle to quantify biology and biogeochemistry of the ice-ocean-atmosphere system in all seasons, especially the undersampled winter.

Because the sea ice is thought to play a role in triggering and modifying water and air column processes, it is critical to establish flow-field measurements both in the euphotic zone and atmospheric boundary layer to constrain flow and mixing into and out of sea ice near the Central Observatory. This allows for chemical and biological budgets, fluxes and reactions to be projected onto the synoptic flow field to fully constrain the local biogeochemical system. This attempt to budget and interpret biogeochemical fluxes and in-situ measurements within the IIR will require a detailed suite of coordinated physical measurements, which define the ambient conditions governing transport, reaction kinetics and biological growth. One benefit of MOSAiC and the Central Observatory is the highly interdisciplinary observational approach, which will provide context for interpreting biological and biogeochemical processes. Critical, coordinated physical measurements should include: Profiles of air temperature, pressure and humidity; LW and SW radiation at ice top and bottom; Evaporation/precipitation at ice-water surface; 3D, low-level atmospheric winds; Profiles of temperature and salinity in the euphotic zone and into the deep ocean; Ekman and geostrophic flow in the euphotic zone; High resolution, diapycnal mixing across the base of the OML or euphotic zone, whichever is deeper, and up to the sea ice base; and Ice properties including structure, light transmission, porosity and permeability, including meter-scale resolution of sea ice cover, floe lengths, and roughness.

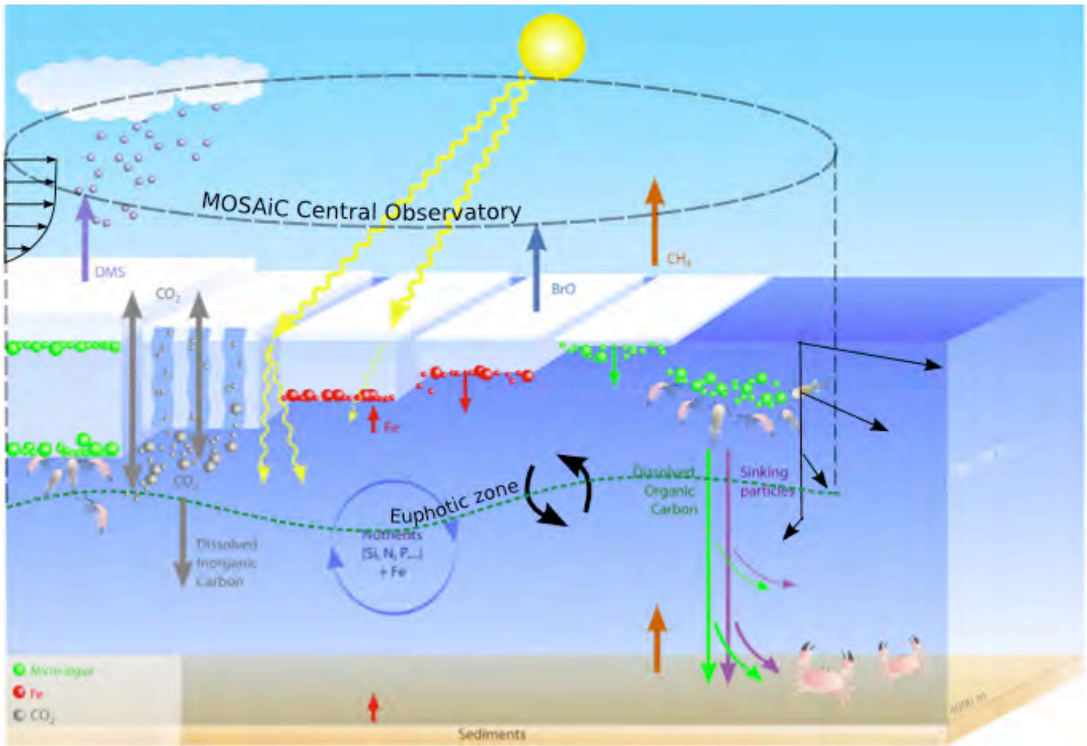


**Fig. 3.3**. A schematic of the Central Observatory focusing on key processes. Colored arrows indicate biogeochemical processes that we aim to observe. Dark arrows indicate flow and mixing processes that should be constrained to determine biogeochemical budgets. After Vancoppenolle et al. (2013).

Biological and biogeochemical processes have spatial heterogeneity due to patchiness of ice structure, microbial communities, and interactions with the upper ocean. Moreover, both the magnitude and direction of biogeochemical fluxes appear to evolve with season and with the advance of ice age from its initial formation to its melt. To characterize the biology and biogeochemistry of the Central Observatory, multiple, spatially distributed measurements will be made within the local domain (<2 km), throughout the annual cycle. To assess lateral effects the MOSAiC distributed network will be used to observe how a select group of properties co-vary with measurements at the Central Observatory (see Section 3.2).

The MOSAiC Central Observatory observations will be designed to accomplish the following objectives:

1. Produce an annual mass budget of organic and inorganic carbon and alkalinity in the IIR, including crystallographic measurements of Ikaite in brine channels. This budget will address recent and longstanding questions related to the net air-ice flux of $CO_2$ caused by sea ice biochemistry in addition to the potential for organic carbon trapping and respiration to $CO_2$, and provide the opportunity to evaluate the sea ice DIC pump hypothesis, which can only be quantified over an annual cycle.
2. Quantify methane accumulation, oxidation beneath sea ice, and air-sea flux. This can address the processes related to the potential for large oceanic fluxes of methane to the atmosphere. Central to determining the magnitude of these fluxes is the recognition that sea ice may retard methane transport while Archaea act to partially oxidize some of the dissolved methane content.
3. Observe the cycle of biogenic gases such as $N_2O$, $O_2$, DMS, Bromoform, etc. in snow, sea ice and under-ice water together with biological variables to understand the underlying biogeochemical pathways of the compounds.

4. Produce both diagnostic and mechanistic measurements of the gas transfer velocity. These measurements will feed directly into the methods required to estimate $CO_2$ and $O_2$ budgets for the Central Observatory and can help determine the drivers and magnitude of gas exchange when fetch is reduced and other turbulence processes lead to air-sea exchange.
5. Produce an annual mass balance and ice-water cycling of macro and micronutrients. This will facilitate an evaluation of the hypothesis, and test mechanisms, for the progressive concentration of nutrients including iron in sea ice for subsequent seeding of the mixed-layer bloom. Characterize vertical fluxes of nutrients among the sea ice, euphotic zone, mixed layer, and deep ocean, in combination with molecular tools to understand recycling pathways.
6. Make oxygen, nitrate and optical measurements from autonomous sensors. Together these measurements can establish whether the sea ice zone on an annual cycle is a net producer of $O_2$ (net heterotrophy) or a net producer of $CO_2$ (net autotrophy), and the nature of their evolution over the annual cycle. In particular the net community productivity will also be coupled with measurements of air-sea gas exchange in the sea ice.
7. Quantify the annual cycle of primary production in sea ice and the upper ocean. The IIR provides an unprecedented opportunity to compare estimates of net community production and net primary production (from e.g. $O_2$/Ar and $^{14}C$) to estimates of particle flux from optical backscatter and beam attenuation measurements or sediment traps that can be periodically deployed and retrieved to obtain both annual net and shorter term resolution.
8. Determine the strength of particle export via the biological pump, including cycling of DOM in the IIR. This will help to rectify long-standing methodological discrepancies in quantifying gas fluxes by implementing coincident methodologies and investigating the output in real time to help constrain inherent biases. Mass balance estimates can help to ground truth the methods.
9. Characterize the spatial distribution of sympagic and planktonic biomass (e.g., ice algae, phytoplankton, microbes, micro- and meso- zooplankton) and determine their biodiversity. Quantify the energy flow and elemental (C,N,O,P) and compound-specific (e.g. amino acids, fatty acids) cycles in the ice/ocean ecosystem. Special focus will be on the energy flow and the elemental and compound-specific cycles within the sea ice and pelagic communities, and the linkages between the two communities through the quantification of important biological rate processes. Important processes include PP (new and regenerated), microbial respiration and remineralization, microzooplankton feeding and growth, and mesozooplankton feeding, respiration, growth, and reproduction. Standing stock measurements of all of the important biological and chemical components are needed to obtain an integrated estimate for energy, elemental, and compound specific budgets. The distribution of organisms in relation to physical conditions (ice, stratification, water masses, etc.) is also important to evaluate the physical-biological interactions that impact production, pelagic retention and vertical export.
10. Determine the seasonal cycles of nutrient stocks, abundance and biomass of important components of the biological communities (e.g. ice algae, phytoplankton, zooplankton), and behavioral (e.g. vertical depth preferences and diel or ontogenic vertical migration) and life history (e.g. reproductive timing and overwintering strategies) patterns.

Measurements to accomplish these objectives will be made through a combination of routine gas and optical measurements from autonomous systems, analysis of routinely collected water and ice samples, vertical net tows, and others. A key feature of the Central Observatory is the availability of laboratory and support facilities to collect and analyze labor-intensive in situ measurements (e.g., nutrients, pigments, POC, DIC, primary production, community respiration, alkalinity, bacteria, phytoplankton and zooplankton community composition, DNA and RNA samples of all communities, reproduction and secondary production estimates). It is of major importance to study the fate of PP (i.e., the carbon and nitrogen energy flow through the sympagic, pelagic and benthic community) using traditional tools (gut content) as well as novel stable isotope techniques and molecular tools. Sediment trap deployments will be conducted to determine vertical fluxes and estimates of how much is retained in the water column and how much is deposited at the ocean floor. Special emphasis should be given to studies of the biological processes in the boundary layer between sea ice and water and ocean floor-water, all narrow habitat zones for intensive biological activity.

These ship-based measurements will play a critical role in providing common calibration references for a large suite of autonomous sensors distributed in and around the Central Observatory, and for building proxies (e.g., calibration of nitrate sensors, chlorophyll fluorescence to chlorophyll concentration, optical backscatter and beam attenuation to POC, optical properties to phytoplankton community composition, acoustic measurements for zooplankton composition). Careful laboratory calibration and cross calibration will help place the entire sensor network into a common reference, facilitating quantitative analyses that employ multiple, coordinated platforms. The proxy relationships allow leveraging of the extensive, but spatially limited, ship-based sampling onto the much more numerous, distributed measurements provided by the autonomous sensor network (section 3.2).

## 3.2 Distributed Networks

Distributed networks of atmospheric, cryospheric, oceanographic, biological, and biogeochemical measurements centered on the Central Observatory are needed to: 1) Observe the characteristic spatial heterogeneity and variability of key properties and processes; 2) Distinguish spatial from temporal variability; and 3) Provide the boundary conditions, spatial context, and advective contribution to observed variability for the Central Observatory measurements and modeling activities. Not all measurements can be made over distributed networks and these autonomous measurements will often be simpler than those made at the Central Observatory. However, the distributed observations will be designed to complement those made at the Central Observatory. Many of the parameters of interest are the same, but the scale of the observations is larger necessitating different approaches and tools. Moreover, the complexity and comprehensiveness of Central Observatory measurements will aid in interpreting distributed network measurements. Ideally, these distributed networks will be operated year-round, but some may be targeted in time to better understand key, season-specific processes (e.g., autumn freeze-up). The distributed networks will provide a “mesoscale” (~5-50 km) perspective on the spatial structure of the system that can be useful for approximating sub-grid-scale processes for models. The scale will be designed to approximate the grid scale for regional climate models (RCMs) and the near-future grid scale of Earth System Models (ESMs).

Distributed **atmospheric** measurements on grid-box-scales are critically important for representing the role and variability of atmospheric processes and their interactions with the ice and ocean surface on multiple-scales. However, autonomous atmosphere measurements are a challenge because ambient conditions adversely impact most measurements of interest. Additionally, atmospheric profiling requires sounding or remote-sensor systems that are not optimally suited for long term, unattended operation in harsh environments. Thus, distributed atmospheric measurements must be carefully considered and designed. At a minimum, four types of spatial atmosphere measurements will be targeted: 1) The spatial distribution of lower-atmospheric state (pressure, temperature, winds); 2) The spatial distribution of atmospheric radiative and turbulent heat fluxes, particularly under heterogeneous surface conditions and during the transition seasons; 3) The spatial distribution of cloud/precipitation systems; and 4) The vertical distribution of aerosol properties such as concentration to help diagnose source regions.

For the **sea ice** the overarching goal is to extend the observations made at the Central Observatory ice floe to characterize the variability of ice properties over the ensemble of floes on the aggregate scale and over a full annual cycle. Four primary areas will be targeted for distributed measurements of ice properties: 1) Snow and ice morphology, including surface topography, snow depth and ice thickness distributions, ice floe size distribution, lead fraction, ridge characteristics, melt pond distributions, and the spatial relations of these features; 2) The partitioning of solar radiation for different ice morphologies, including spectral surface albedo; 3) Mass and freshwater balance in all seasons; and 4) Ice motion, deformation, and internal stress.

**Ocean** variability in space can be important for the vertical transfer of heat, momentum and nutrients, with important gradients near the bottom of the sea ice, the bottom of the ocean mixed layer, and in close proximity to other features including ridges, leads, ice edges, etc. Additionally, the effect of transient events can manifest on important spatial scales that should be resolved. Specific target areas for spatial characterization, include: 1) Upper ocean micro-structure and state (T, salinity), including freshwater budget; 2) Upper ocean turbulence profiles; and 3) Heat flux terms including solar input and vertical flux at the base of the ocean mixed layer

Distributed **biological and biogeochemical** measurements are a challenge as many of these measurements require laboratory analysis of samples. However, it is important to measure the spatial variability of certain biota, biodiversity, chemical species, and nutrients in the upper ocean, ice, and lower atmosphere, when possible. In particular, spatial measurements are needed to understand how biological and biogeochemical processes are impacted by spatial variability in ice properties, leads, solar penetration into the ice and ocean, turbulent mixing in the ocean, and others. Spatial measurement of atmospheric gases can provide insight into aerosol sources and mechanisms for air-sea interaction. In some cases, ice cores and upper ocean samples should be taken manually on at least a monthly basis at distributed locations as these cannot be taken autonomously. These samples can be analyzed at the Central Observatory for a number of chemical, physical, biological, and biogeochemical properties.

To obtain the needed observations, distributed measurements will be made using a variety of different platforms. For scientific and logistical purposes many of these measurements will be made at the same locations and/or from the same platforms. Thus, the network will be described here in terms of the general platforms that will be utilized.

*Remote station nodes*. The outer boundary of the distributed networks will be defined by a set of nodes at the four corners of a ~50 km box centered on the Central Observatory (Figure 3.4). A fifth, identical node will be established near the Central Observatory. Each node will drift with the ice and include a suite of multi-disciplinary, buoy-based measurements, utilizing existing buoy network technologies that have, in some cases, been in operation for a number of years. Some of these systems are essentially inverted moorings, anchored at the ice surface, rather than the sea floor, with profiling elements suspended below. Buoy systems will include some combination of Ice Tethered Profiler (ITP), Ice Tethered Micro-mooring (ITM), Ice Mass Balance (IMB), Autonomous Ocean Flux Buoy (AOFB), O-Buoy, Ice-Atmosphere-Ocean Observing System (IAOOS), Surface Radiative Flux buoy, and potentially others. Some of these buoys have been deployed jointly in the past and will be improved by new atmospheric, biological and biogeochemical sensors. Together this set of buoys will provide a wide range of the necessary distributed measurements (Table 3.1).

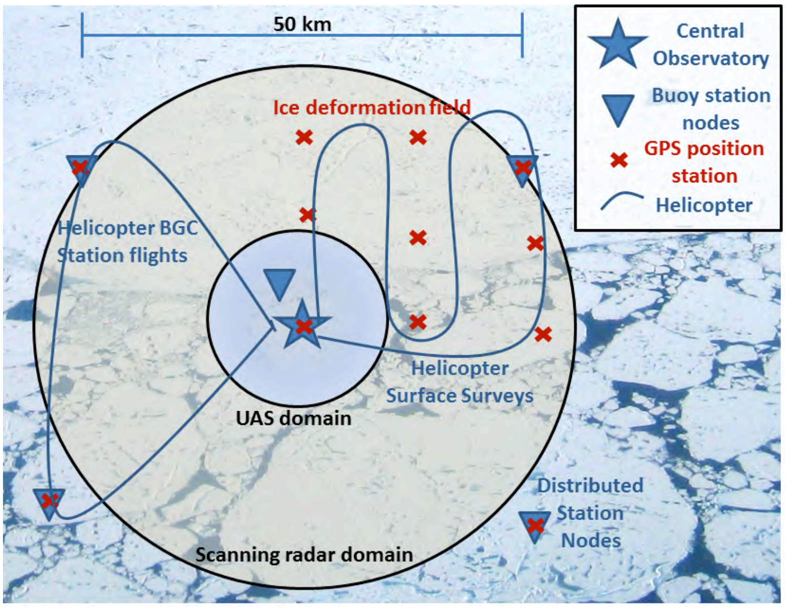


**Fig. 3.4:** Schematic of distributed network surrounding Central Observatory.

One limitation in existing technologies is the ability to autonomously measure atmospheric profile information and surface radiative and turbulent fluxes; it is hoped that these technologies will be available and robust for use during the MOSAiC time frame. For example, the iAOOS program is developing buoy-based lidar systems that might provide information on cloud presence and aerosol profiles under certain conditions. In addition to the primary nodes, a set of approximately 12 intermediate nodes will also be established with simple GPS positioning sensors to better observe and resolve details of sea ice deformation and divergence on smaller scales (see Figure 3.4). It is anticipated that the five primary node stations will be visited via helicopter flights from the Central Observatory about 2-4 times during the year, as possible.

**TABLE 3.1** Measurements and platforms at the remote station nodes.

| **Measurement** | **Platform** |
|---|---|
| Ocean state (CTD) | ITP, ITM, iAOOS |
| Ocean momentum, heat, salt fluxes | AOFB |
| Ice thickness, snow depth | IMB, iAOOS |
| Ice T profile | IMB iAOOS |
| Basic surface meteorology (P, T, q, wind) | IMB, O-Buoy, iAOOS |
| $CO_2$, $O_3$, BrO | O-Buoy |
| Cloud presence | iAOOS |
| Spectral and/or broadband radiative flux, Photosynthetically Available Radiation | ITM |
| Transmitted solar flux | IMB |
| Nitrate, chlorophyll sensors | ITP, IMB |
| Acoustic Doppler current profiler | ITP-type mooring |
| Automated water sampler | ITP-type mooring |
| Visual imagery – camera | IMB |
| Position | All |

*Helicopter flights.* Maintenance of the distributed network, as well as some specific measurements within the distributed network domain, will be made using a helicopter that is stationed with the Central Observatory ice breaker. Depending on the local conditions and the quality of measurements coming from the buoy suites at the remote station nodes, helicopter flights will be used to visit (or simply evaluate by air) one or more of the remote station nodes at a time. Such visits will be particularly important if specific issues are identified at these nodes that could realistically be addressed. Ideally each node will be visited/evaluated 2-4 times during the year, and/or as needed based on operational conditions, in order to maintain robust measurements.

Helicopter sorties are also needed to collect distributed ice and upper-ocean samples on a weekly to monthly basis for subsequent biological and biogeochemical analysis at the Central Observatory. Ideally these sampling missions will coincide with visits to the remote station nodes to allow for BGC sampling to be co-located with other continuous measurements. Helicopter surveys will also be important for characterizing the spatial distribution of surface properties over scales of 10s of km. Such surveys will be season dependent, ranging from every couple of weeks in the middle of winter to ideally multiple times per week during the melt season. For this purpose, the helicopter will be outfitted with visible and infrared cameras, radars, and radiometers that are able to distinguish surface types. Ice thickness will be measured using an electromagnetic ice thickness sensor. Additionally, measurement systems exist for sampling atmospheric meteorology and aerosol concentrations from helicopter platforms. The effectiveness of this approach versus that from unmanned aerial systems (UAS) will be considered, but some combination of the two approaches will likely be needed to cover the different scales of interest. All helicopter operations will be outside of cloud, either in clear sky conditions or below cloud base.

*Scanning instruments*. Some atmospheric measurements can be obtained over scales of multiple 10s of kilometers using scanning remote-sensing instruments stationed at the Central Observatory. In particular, a scanning X-band radar system installed onboard the icebreaker can be scanned in a variety of ways, including a low-angle surveillance type scan pattern that will provide approximate snapshots of the two-dimensional cloud and precipitation field surrounding the radar at ranges of 50 km or more depending on the conditions. Similarly, scanning Doppler lidar measurements will provide information on 3D wind fields in clear air below clouds at scales of up to 10km around the Central Observatory.

*Unmanned Aerial Systems (local).* UAS technologies are currently being developed and deployed for a number of applications. Capabilities are evolving rapidly and offer an exciting potential to obtain spatial measurements around the Central Observatory on a quasi-operational basis that are more cost effective than manned aircraft operations. With these systems there is a trade-off between ease of operation and cost (which often means smaller systems) and spatial range (which often means larger systems). The intention is for the MOSAiC UAS program to be locally operated, meaning that aircraft will be locally launched and recovered either from the deck of the ship or from the adjacent ice. Thus the specific UAS platforms used must be smaller systems that have a relatively shorter range, typically less than 5 km. These systems will be used on a periodic basis (weekly at minimum) to provide important measurements of the spatial and vertical variability of key parameters.

Four primary science missions will be addressed using UAS: 1) Ice and snow surveys using downward looking visible and infrared photography (1/week); 2) Aerosol number concentration profiling (1-3/week); 3) Spatial and vertical radiative fluxes, including spectral surface albedo (1-3/week); and 4) Spatial near-surface turbulent energy flux measurements (1/week). All missions will include basic meteorological measurements (temperature, pressure, winds) to provide important spatial information on atmospheric structure and context for other measurements. Additionally, some measurements will complement the helicopter activities, such that an appropriate balance between the two should be developed. While technologies for de-icing UAS are under development and measurements in clouds would be quite useful, these are not planned at present. Thus, current plans are to fly below clouds and/or in clear sky conditions. For science mission #4, the UAS platform may be the only way to measure near-surface turbulent heat fluxes in open ocean, marginal ice zones, and during initial stages of widespread freeze up. Fixed platforms are not ideal for this purpose because they disturb the delicate environment and often create local turbulence that inhibits successful measurements.

*Autonomous Underwater Vehicles/Gliders*. Autonomous measurements in the ocean are becoming more sophisticated and widely used for sampling spatial domains and should be routinely used to characterize the domain around the Central Observatory. These robotic platforms are well-suited for routine profiling of physical and some biogeochemical variables, including temperature, salinity, velocity, turbulence, oxygen, nitrate, chlorophyll and CDOM fluorescence, optical backscatter and the subsurface light field. Although restricted (by power and weight) in payload, these platforms provide a cost-effective means to achieve broad distribution while resolving the relevant temporal and spatial scales.

Mobile assets also include both long-endurance gliders and faster, propeller-driven autonomous underwater vehicles (AUVs). Both can navigate from point-to-point on survey patterns while following the observatory's drift. These platforms provide excellent spatial resolution, complementing the time series collected by ice-based ocean profilers. Mobile platforms will collect high-resolution sections spanning the entire ~50km sampling region, providing a means to bridge the spatial gaps between buoy nodes. Gliders and AUVs can also be employed in an adaptive mode, directed to conduct smaller, rapidly-repeated synoptic surveys focused on specific regions or events, such as leads. These missions would be informed by analyses of real-time data from both ship-based and autonomous sensors.

Autonomous platforms have finite endurance (months to years) and employ sensors that benefit from periodic calibration. The Central Observatory provides a local base for conducting deployment, recovery and service operations. Instruments that malfunction, reach the end of their endurance or drift out of position can be recovered and replaced. This allows MOSAiC investigators to maintain continuous, 4-D sampling from a dense sensor network. Additionally, the Central Observatory offers laboratory space in the field that is crucial for developing the proxy relationships that are necessary to interpret the measurements from a network of autonomous platforms in a consistent fashion.

### 3.3 Coordinated Activities

Observations over synoptic scales (100-1000+ km) are highly desired to provide pan-Arctic context and information on large-scale variability in the Arctic system. Moreover, measurements near the edges of the Arctic domain are important as a source of boundary conditions for regional modeling activities. Year-to-year variability is also of high interest. Since the list of core MOSAiC activities must be limited, the program will rely on coordination and cooperation with other Arctic observing activities to capture large-scale and inter-annual context. There are numerous ongoing and planned Arctic observing activities by a variety of nations and agencies that will benefit from and support MOSAiC in this regard. Moreover, it is anticipated that during the MOSAiC timeframe there will be enhanced observational activities in coordination with the WWRP Polar Predictability Project’s Year of Polar Prediction (YOPP, www.polarprediction.net). MOSAiC will endeavor to coordinate and collaborate with these programs for the maximum benefit to all. Specific potential activities will be outlined here, while detailed coordination plans will be developed as possible in the future.

*Ships and Ice Stations*. Additional observatories that include detailed disciplinary or inter-disciplinary measurements offer the opportunity for comparisons of process-level information in different locations, conditions, and times of year. Some of these may provide critical profiling information in both the atmosphere and ocean, while some may target very specific physical or chemical processes. Additionally, some of these platforms may assist in deployment/recovery of observational resources or access to the MOSAiC Central Observatory. Specific potential collaborations in this regard include:

- Russian drifting station program: For many decades Russian drifting ice stations have been installed in the Arctic sea ice. More recently these stations have evolved to include a variety of observations in the upper ocean, sea ice, and lower atmosphere. It is anticipated that a drifting station will be deployed during the MOSAiC time frame.
- Japanese marginal ice zone studies: Approximately every 2nd year the Japanese RV Mirai makes measurements in the open ocean and marginal ice zones in the Beaufort and Chukchi Seas. Their cruises include measurements from C-band radar and radiosondings to capture the large-scale meteorology, along with measurements of upper ocean properties and surface-air fluxes.
- Periodic icebreaker missions to the Arctic are also made using the Canadian RV Amundsen, Korean RV Araon, Chinese RV Xue Long, Swedish RV Oden, U.S. Icebreaker Healy, and others, with a wide range of scientific foci.
- A number of periodic or one-time observational activities are planned for the central Arctic during years leading up to MOSAiC that will contribute towards the project’s scientific design and provide initial perspectives on many aspects of the interdisciplinary system. An abbreviated list of these includes: ACSE, PASCAL, N-ICE, NPEO, TRANSSIZ, SIOS, ONR MIZ and Sea State.

*Buoy programs*. Multiple programs deploy buoys on a yearly basis in the Arctic Ocean and ice pack, many of which are coordinated via the International Arctic Buoy Program (IABP). A number of these buoys will be used to comprise the MOSAiC distributed network of observations. It is anticipated that additional buoys, both similar to those used in the MOSAiC network and others, will be operational during the MOSAiC time frame. These will offer information on spatial variability that reaches well beyond the ~50km, model-gridbox perspective of the primary MOSAiC constellation.

*Satellites*. MOSAiC offers a unique, two-way interaction with the satellite community. The surface-based observational constellation is designed to facilitate satellite evaluation activities. For example, the distributed network of ice thickness, snow depth, surface type, and ice motion measurements on multiple scales (1-50 km) and over a full annual cycle will offer unique verification data sets for satellite sea ice retrieval algorithms. With this extensive opportunity for evaluation, satellite products will be more effective for up-scaling local observations to regional and basin scales. Satellite observations also offer unmatched spatial coverage for critical parameters such as sea ice coverage, ice motion, and some atmospheric parameters. High- and moderate-resolution satellite imagery from visible, near-infrared, and microwave channels, in addition to high-resolution synthetic aperture radar on multiple scales, will provide a detailed characterization of sea ice concentration and extent across the MOSAiC domain and beyond. Some information on ice thickness and snow depth can be derived from laser and radar altimetry. Satellite observations of sea ice motion will provide critical context for the large-scale drift and deformation of the ice pack, and will be useful for understanding the MOSAiC drift trajectory. Satellite platforms can also provide important spatial structure on atmospheric properties such as clouds, aerosols, and radiative fluxes as the conditions warrant. Many of the appropriate sensors for such measurements are on A-Train satellites that unfortunately only make observations as far north as 82 degrees; thus, the anticipated MOSAiC drift track may not always be within the domain of these satellites.

*Manned aircraft*. Fixed-wing aircraft offer unique observational abilities in terms of spatial coverage, profiling capabilities, and instrument payload. They allow for in situ measurement of cloud microphysical properties, gases and aerosols, radiometric profiles, spatial structure of the ABL, sea ice thickness surveys, surface albedo, and other key parameters. The presence of the MOSAiC observational constellation in the central Arctic will provide a nice opportunity, and incentive, for coordinated aircraft-based campaigns in the region. Potential aircraft missions may be conducted by the Alfred Wegener Institute (using the Polar 5/6), the UK Facility for Airborne Atmospheric Measurements (FAAM), the US NASA, and others. For example, in the past AWI has flown the Polar 5 on inter-disciplinary missions across the Arctic and over the sea ice as part of PAMARCMIP.

*Permanent Observatories*. Ringing the Arctic Ocean is a collection of land-based observatories that have sophisticated suites of atmospheric and terrestrial instrumentation, in many cases similar to those proposed for the MOSAiC Observatory. Additionally, many of these stations launch twice-daily radiosondes, which will serve as critical boundary information for pan-Arctic regional modeling studies that target central Basin processes and large-scale linkages. Coordinated by the International Arctic Systems for Observing the Atmosphere (IASOA) network, these observatories will serve as a critical means for linking MOSAiC observations to operational, long term Arctic observations.

### 3.4 Intensive Observation Periods (IOPs)

IOPs will be designed to focus on specific processes and times of the year that are particularly useful for model development. These periods will include additional and enhance measurement approaches that extend beyond the long-term, persistent MOSAiC operational activities. These periods will provide important depth to the MOSAiC program via observations that are too intensive to maintain for the full duration of the program. The targeted IOPs will benefit from the context that is provided by the continuous, year-round measurements. Further planning is required in this area, in particular to coordinate external resources; However, potential IOPs include: Contrasting “In ice” versus marginal ice zone versus “out of ice” conditions using coordinated observing platforms; the melt onset and freeze onset; biological productivity blooms; critical periods for vertical ocean heat transport; cloud transition seasons; mid-winter energy budgets; and others. Some of these activities may be accomplished via coordination with aircraft missions (AWI, UK-FAAM, NASA), or other ships (Mirai, Araon, Xue Long, Oden, etc.). Additionally, a regional modeling IOP would greatly benefit from additional atmospheric soundings such as a network of periodic dropsondes that could be deployed using long-range UASs like the GlobalHawk (Intrieri et al. 2014). For example, it would be highly desirable to have a dropsonde array pattern every 2-3 days for a continuous month-long period. Such dropsondes would provide critical large-scale forcing information for regional and local modeling studies.

### 3.5 Drift Track and Considerations

One central aim of MOSAiC is to study the interaction of sea ice with the ocean, atmosphere, and biosphere over a full annual cycle and throughout the full sea ice life cycle from its initial formation through melting. These baseline science objectives must be considered when designing the installation point and drift track for the Central Observatory. Ideally the MOSAiC deployment will last for at least a full year to make observations in all seasons, including a full continuous observation of the transition from the end of melt into freeze up at the beginning and end of the observational campaign. To capture the full sea ice life cycle, the drift trajectory will begin in September adjacent to an open ocean area, observe the autumn freeze, then drift with the growing and deforming FYI throughout the following year. The trajectory will end, ideally the following October, in an area where the ice cover either melts completely, is ejected from the central pack ice, or persists to become multi-year ice the following year. This drift trajectory differs from most earlier field campaigns, which were typically established on the thickest available MYI to allow for a stable observational base from the beginning of experimental setup. In addition to the above requirements, the drift trajectory should follow a route that leads through atmospheric and oceanic conditions that are typical for the bulk of the FYI that currently exists in the Arctic. Thus, it should be far away from coastlines, which will allow for air-ice-sea interactions that are typical for the oceanic climate that governs much of the Arctic ice cover.

Drift track considerations will be one of the largest challenges for MOSAiC because: 1) It may be difficult to find a trajectory that will last for a full year in stable ice cover; 2) It is difficult to forecast the ice growth and drift patterns for future years; and 3) The optimal drift tracks to achieve the scientific objectives may be logistically challenging. To accommodate these concerns, the initial plans presented here will remain flexible to adjust to evolving conditions and limitations. Two approaches are considered for preliminary planning of the drift trajectory: sea ice drift model studies and drifts of prior ice camps.

Preparatory modeling activities can be important for suggesting the optimal drift trajectory. The Russian Arctic and Antarctic Research Institute has been operating drifting ice stations for many decades and has vast experience with planning drift tracks. One model they use is a coupled atmospheric surface layer – sea ice – ocean model called AARI-IOCM (Kulakov et al. 2012). The model is adapted to Arctic Ocean conditions and geography. It is forced by NCEP/NCAR reanalysis for surface pressure and temperature, while including climatological clouds, moisture, precipitation, ocean temperature, and salinity. Drift trajectory calculations starting in late September have been made with this model for the years from 2000 to 2012. Comparisons have shown that this model can successfully reproduce basic sea ice conditions and ocean circulations in the Arctic Ocean.

Simulated ice drift trajectories for the 12 years starting at a number of different locations are shown in Figure 3.5. Each panel also shows the length of the mean safe drift (i.e., the point where the trajectory meets 85°N) while the minimum simulated drift length for these years is given in parentheses. It can be readily seen that the longest drift trajectories are accomplished by starting between 150-180°E, and south of 86°N. Even these drifts often lasted for less than one year, although depending on ice conditions the drift could continue well south of 85°N. The average spatial modeled drift trajectory of all years is given in Figure 3.6.

These modelled ice-drift trajectories are largely consistent with recent Arctic drifting deployments, such as the Russian drifting stations, ice buoys, and the Tara expedition. Figure 3.7 shows the September minimum sea ice extent in 2011 with a number of these drift tracks overlaid. Together the modeled and observed trajectories suggest that the chances of obtaining a full year-long drift increase greatly if the deployment is in the northern East Siberian Sea. Deployments (i.e., NP-36 in 2008-2009 and NP-38 in 2010-2011) and model simulations from this region drifted towards the North Pole via the Transpolar Drift. Deployments further west in the Laptev Sea (such as the 15-month Tara drift in 2007-2008) may also provide a year-long drift.

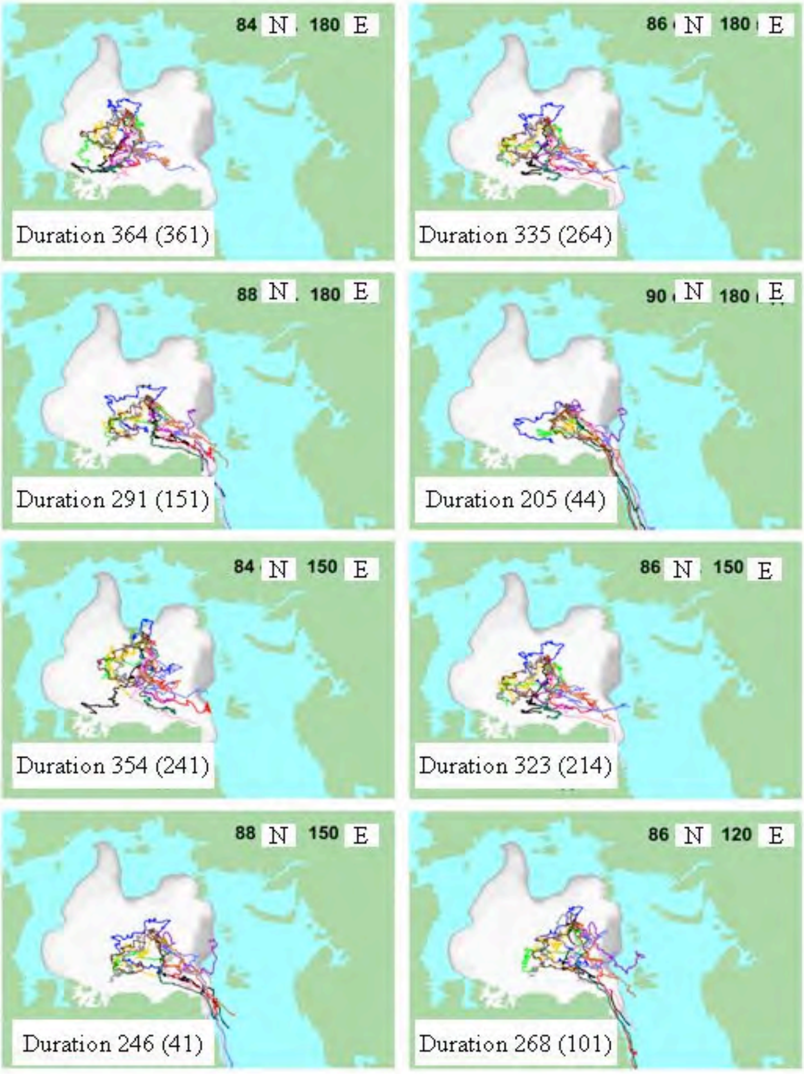


**Fig. 3.5:** Simulated drift trajectories starting from the location indicated on each panel for the years from 2000-2012 (different colored lines). The mean (minimum) trajectory length in days is given in each panel. Trajectory end is denoted by crossing 85 degrees N latitude.

Based on this information, the initial plan for a drift track that would fulfill the MOSAiC science objectives is to deploy in the East Siberian Sea and drift along the Transpolar Drift through the North Pole region and towards Fram Strait. There are a number of benefits to this approach. Such a drift would likely be the longest possible, would provide the opportunity to sample FYI over a full year, and would provide nice sampling in the central Arctic ice pack. It would also allow for sampling on both the Pacific and Atlantic sides of the Arctic and offer the possibility to coordinate observations with numerous international observing assets. Such a track would also have complications. This drift track will mean that the Central Observatory will be far from land during some parts of the deployment, making resupply challenging. Starting in newly forming FYI will mean that the ice pack is thin and weak, making deployment of instrumentation on the ice difficult until later in the winter season. There could also be enhanced ice dynamics in the thin ice. To mitigate some of these difficulties, it may be preferable to initially deploy the observatory near the ice edge, directly adjacent to ice that persisted through the previous year’s melt cycle, with ample access to nearby newly forming FYI.

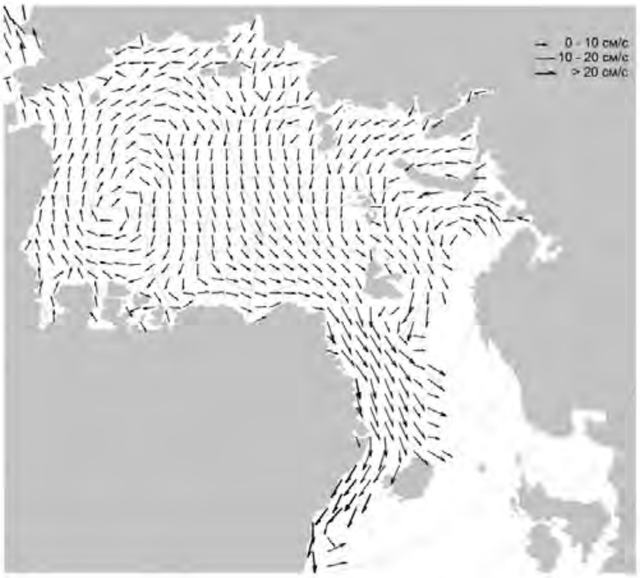


**Fig. 3.6:** AARI-IOCM average ice drift in Arctic Ocean (2001-2012)

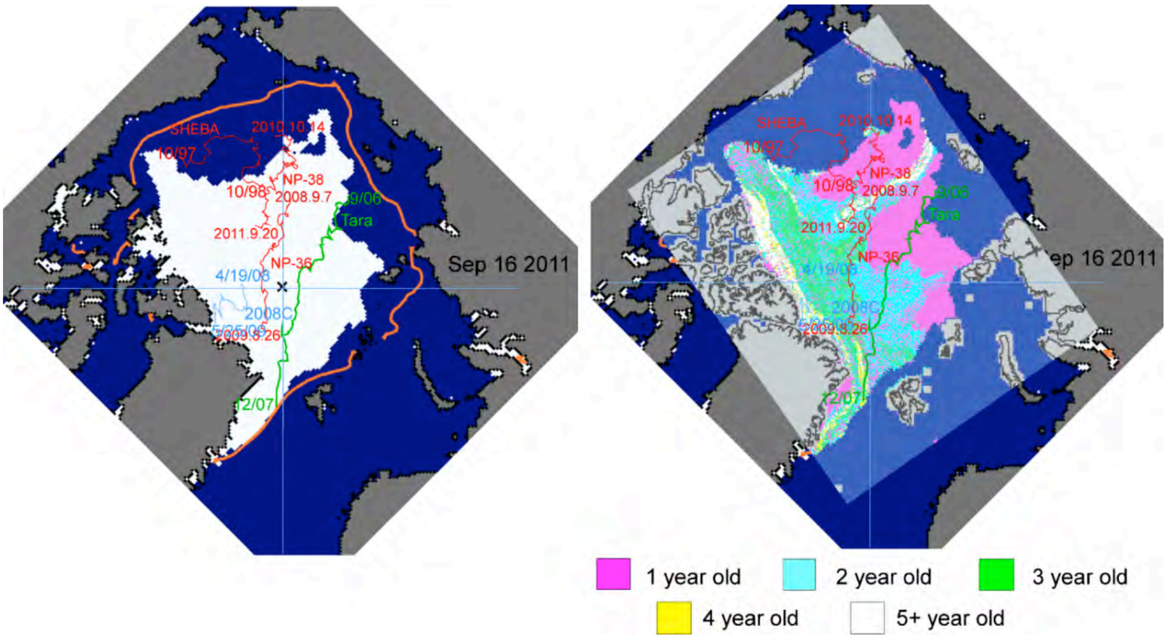


**Fig. 3.7:** September 2011 sea ice extent (left) and ice age (right) overlaid with select drift tracks form ice buoys, NP-stations, and Tara. Ice extent courtesy of NSIDC; ice age courtesy of J. Maslanik/NSIDC.

Other deployment locations have important limitations with respect to the MOSAiC science objectives. For example, deployment on MYI near the Canadian Archipelago might provide strong and stable ice, yet would not provide much insight into the FYI processes that now dominate the Arctic. An autumn deployment in the Beaufort Gyre could provide access to FYI, but would have similar logistical challenge to the Transpolar Drift approach and would likely not last a full annual cycle. Moreover, the Beaufort Gyre is already arguably the most studied region of the Arctic Ocean.

Regardless of the specific drift track, site access will be difficult in a FYI environment that may be far from coastlines. Accessibility is an important consideration for resupply, safety, and scientific coordination. Aircraft access will be challenging due to the potentially thin ice, although a local ice runway may be possible in winter. Possible land-based resupply airports would be on the Siberian islands of Ostrov Kote’nyy and Severnya Zemlya, Alert in Canada, and Svalbard. The middle portion of the Transpolar Drift route would be approximately equidistant from these land-based sites. Other options for resupply could be coordination with other vessels that will be in the Arctic. The logistical implications of a possible multi-month gap between resupply opportunities must be considered.

Clearly, while the Transpolar Drift track would be the optimum choice for addressing MOSAiC science objectives, many key logistical difficulties will need to be resolved before such a track can be finalized. Coordination and consultation with the Forum for Arctic Research Operators (FARO) throughout this decision-making process will be critical. Furthermore, additional model simulations with state-of-the-art sea ice drift models will need to be performed in the time leading up to the deployment to provide the best possible guidance for deployment.

## 4. SYNTHESIS ACTIVITIES

The ultimate scientific goals of MOSAiC can only be accomplished by coordinated observational, modeling, and synthesis activities that support improved process-level model representations and lead to enhanced model forecasting abilities. MOSAiC will employ a hierarchical, multi-tiered approach as a means for synthesizing and integrating information and placing it in the broader regional, global, and climatological context. High-resolution and process models are most appropriate for interfacing with the detailed observations made across the MOSAiC constellation, while regional and global models provide the ability to upscale this detailed information to pan-Arctic and global scales. Multi-scale model activities will help bridge the inherent spatial and temporal limitations of the observational campaign and are a necessary step in answering the question: How does the MOSAiC process-study improve the ability to assess possible linkages of the changing central Arctic with hemispheric weather and long term Arctic climate? Building on the MOSAiC observations outlined above, and the variety of observational analyses they will support, specific modeling elements for MOSAiC include: preparatory and operational modeling activities, process-modeling, regional climate modeling, and large-scale model analysis. Each of these will be discussed in distinct sub-sections.

One key design element for MOSAiC observational, model, and synthesis activities will be coordination with the WWRP Polar Prediction Project (PPP) via the Year of Polar Prediction (YOPP). The goal of YOPP is to “Enable a significant improvement in environmental prediction capabilities for the polar regions and beyond, by coordinating a period of intensive observing, modelling, prediction, verification, user-engagement and education activities.” To achieve the goal, YOPP will greatly benefit from the advances of process-level understanding provided by MOSAiC to help improve model parameterizations. In turn, MOSAiC experimental design can benefit substantially from the coordinated experimental modeling activities performed on process to weather forecast scales in the pre-YOPP period. Thus, strong coordination with PPP/YOPP, and similar broad integrative activities, is critical for the MOSAiC design.

### 4.1 Preparatory and Operational Model Activities

Preparatory model activities will be central in designing and specifying the MOSAiC observational field program. These activities will address two primary targets related to the observational activities: planning for the drift trajectory based on an assessment of sea ice life cycle analysis from model simulations; and an assessment of the key observations that should result from MOSAiC's field program that will have a large potential to improve current models. Additionally, preparatory model activities will serve as a reference point for the current state of the art in Arctic climate-system modeling against which progress resulting from MOSAiC's field program can be determined. This section outlines in more detail the aims and strategies of these individual modeling activities.

#### *Informing the drift trajectory*

Identification of an ice drift trajectory that will best fulfill the MOSAiC drift track requirements (Section 3.5) is only possible through dedicated model simulations that can represent the significant changes that have occurred in the Arctic Ocean over recent years. Such model simulations will be based on both regional and global models that employ data assimilation to best represent the current state of the Arctic climate system; optimized methods for coupled data assimilation are explored in PPP and will aid this effort. Through ensemble simulations with different atmospheric forcings, including both coupled simulations with a freely evolving atmosphere and simulations with an ice-ocean model driven by atmospheric circulation patterns as observed throughout the past decades, a statistical distribution of possible drift trajectories will be derived. These will then be analyzed regarding the oceanic, atmospheric and ice conditions that a particular parcel of sea ice encounters along those trajectories throughout its life cycle. Such analysis help in identifying the drift start and projected trajectory.

*Identifying critical observational variables*

Progress in understanding air-ice-sea interactions in a changing Arctic will be largely based on improved representation of key processes in numerical models. This then allows for a quantitative assessment of the interaction of these processes in the controlled environment provided by model simulations. Often, a realistic model representation of key processes is hindered by a lack of sufficient, targeted observational data that can be effectively used to derive new parameterizations and assess their quality. In particular, Arctic-wide or even global model simulations that are key to understanding process interactions are based on grids that are large compared to the length scale of many relevant processes. For example, models are (and will be in the foreseeable future) unable to realistically represent the distribution of open water and individual ice floes. The same holds for the representation of leads and cracks in the ice, the distribution of ridges, the re-distribution of snow on the ice, and surface melt ponds, among others. For all these properties, and related processes such as turbulent exchange of heat, moisture and momentum, models employ parameterizations to represent the integrated impact of small-scale processes on the scale of model grid cells.

To guide MOSAiC observational priorities and specifications, preparatory model simulations have been, and will be, conducted to identify those processes that are least realistically represented in current models and that most strongly influence the results of the simulations. For these activities, simulations will be carried out that span the entire range from eddy-resolving to global. Some of these activities will be done as inter-model intercomparison projects coordinated by the GEWEX Global Atmospheric System Study (GASS). The higher-resolved simulations will be used to identify the impact of small-scale fluctuations in, for example, surface properties on length scales that are typical for the lower-resolved models. Through a process chain from the highly resolved models to global models, observational requirements can be determined regarding accuracy, spatio-temporal resolution, specific parameters, etc. This kind of preparatory sensitivity study based on statistical distributions of key variables will be an important step forward compared to classical sensitivity studies in which only a mean value of a specific parameter is changed to determine model sensitivity.

Identifying the parameters producing the greatest sensitivity will also require unique evaluation techniques that emphasize process relationships rather than prognostic capabilities. That is, a model must be able to produce a similar response to a given forcing that is evident in observations, and this response may be dependent on a key system parameter (e.g., thermal conductivity of ice, snow depth, atmospheric transfer coefficient, etc.). Such a statistical approach may be the only way to evaluate critical parameters in climate models given the high variability and low predictability of the Arctic. Recent studies (e.g., Sterk et al. 2013; Pithan et al. 2013) have begun to apply some of these techniques for evaluation of models' capabilities to represent Arctic processes. These studies, among others, point to the need of evaluating the coupled atmosphere/sea ice/ocean system since the coupled response often differs from the uncoupled one.

*Defining a reference point for model improvements*

In addition to sensitivity studies, numerous preparatory model simulations will be used to quantify shortcomings of today's models. Such quantification of model shortcomings is a challenging task because of the inherent internal variability of the Arctic climate system and the lack of observations to use as reference. Differences between model simulations and observations of large-scale properties of the ice pack, for example, are often explicable by internal variability. This is particularly true for the assessment of trends.

Process-oriented model inter-comparison projects are ongoing and will be further developed in collaboration with GASS to attract attention to specific Arctic related issues. These GASS projects typically target a specific model problem and utilize observations and detailed process models such as LES and CRMs to test the parameterizations used in weather forecast and climate models. An ongoing activity is an idealized single column model (SCM) cases study of the Lagrangian transformation from marine to Arctic air revealing model problems in cloud, radiation and turbulence parameterizations in interaction with the surface. Developing a coupled ocean-ice-atmosphere single-column model would greatly facilitate such studies.

Specific shortcomings of model simulations will be more clearly identified by analyzing statistical relationship between variables that are physically coupled. For example, simulated sea ice drift will be analyzed as a function of modeled ice thickness, ice concentration, and normalized wind forcing, and the statistical distribution of these multi-dimensional relationships will be compared to corresponding relationships derived from past observations. A similar statistical analysis will be carried out for the analysis of other process relationships such as the seasonal distribution of surface albedo, ice thickness distribution as a function of ice age, response of sea ice concentration to normalized wind forcing, and many other processes in the ice, ocean, and atmosphere. This type of focused evaluation of statistical relationships against observations will reveal model shortcomings that are clearly related to a lack of realistic process representations as opposed to simply being artifacts caused by model internal variability.

*Operational modeling*

Real-time modeling will be required to support safe operation of the drifting constellation of MOSAiC observations. In particular, this operational modeling will help to forecast the evolving drift trajectory to provide support for logistical operations and site access. This forecasting will also help to coordinate intensive observation periods and/or other activities that are coordinated with collaborating observational initiatives. Additionally, operational models will help guide the scientific foci of enhanced observations. Routine radiosonde observations, at a minimum, will be operationally uploaded to the Global Telecommunications System to facilitate assimilation into operational models to best constrain present conditions. Operational modeling will be done in coordination with YOPP-affiliated modeling centers.

## 4.2 Process Modeling

Process and limited-domain models are the most direct way to link the detailed, process-based MOSAiC observations with larger-scale model development and analysis activities. Additionally, when evaluated using observations, these models can support important process-based understanding that is not possible through observations alone. Multiple model types fit into this category, including Single Column Models (SCM), Large Eddy Simulation (LES), and Cloud Resolving Models (CRM). In particular, SCMs are an ideal tool to study the behavior of sub-grid-scale parameterizations in controlled and specified conditions. They allow for “off line” testing of parameterizations and sensitivity studies. LES and CRM can be conducted in multiple configurations but importantly provide high-resolution (eddy resolving) simulations of processes that occur on small scales that are typically much smaller than the grid boxes for regional and global models. These models are ideal for examining processes such as three-dimensional fields of small scale turbulence.

As an example, LES simulations are able to resolve detailed processes related to Arctic clouds, horizontal and vertical turbulence, advection, radiation, and heat fluxes. Two specific approaches are possible. First, in a traditional LES approach, with periodic boundary conditions, simulated parcels can be effectively considered from an idealized Lagrangian framework. Advection and boundary conditions can be specified in an idealized way or forced by observed data or reanalysis. Such an approach is useful for understanding, for example, vertical mixing of heat and moisture relative to cloud formation (Solomon et al. 2014). Importantly, while certain aspects of these model simulations can be evaluated relative to observations, such as the evolution of the cloud liquid water path and temperature, the model is able to provide consistent information on other parameters that cannot be directly observed, such as vertical fluxes of moisture.

In a second approach, nested mesoscale model domains can be employed where successively smaller, and higher-resolution, domains operate within larger domains. The model outer domain is initialized and forced at the boundaries with reanalysis data, allowing for the modeling system to be influenced by realistic transient synoptic-scale weather systems. The inner domains are able to resolve and simulate successively smaller-scale processes. A central domain can be run at LES scales to resolve detailed processes; this domain can be centered on a given observation site to allow for detailed statistical comparisons with vertically-resolved observations. The benefit of this nested approach is that it provides a self-consistent, two-way linked means for scaling from regional scales down to scales that are much smaller than a regional climate model grid box. Such an approach has proven successful for simulating long-lived Arctic mixed phase stratocumulus clouds and examining the interplay of larger-scale forcing and small-scale turbulent and entrainment processes (Solomon et al. 2011).

For MOSAiC, case studies will be defined for targeting specific processes. For these cases, large-scale eddy simulations over domains of approximately 25 km x 25 km (similar to a RCM grid cell) will be conducted with these high spatial and temporal-resolution modeling tools. Where possible, model inter-comparisons will be established to examine the impact of different model specifications for key processes.

### 4.3 Regional Climate Modeling

For quantitative estimates of future Arctic climate change it is necessary to improve the understanding and representation of the underlying mechanisms governing internally generated climate variations and their interplay with anthropogenically induced climate forcers. In a review article, Maslowski et al. (2012) capture the essence of the problem: “A system-level understanding of critical Arctic processes and feedbacks is still lacking. To better understand the past and present states and estimate future trajectories of Arctic sea ice and climate, we argue that it is critical to advance hierarchical regional climate modeling and coordinate it with the design of an integrated Arctic observing system to constrain models.” As stated, regional modeling, linked with observations, is a critical tool. Regional Climate Models (RCM) offer an important link between higher resolution process models and global models. They have the ability to dynamically downscale, enhance resolution, and minimize impacts of lower-latitude errors associated with global models or to be used for historical periods utilizing reanalysis products as boundary conditions. Their higher resolution allows for a more detailed evaluation with the MOSAiC distributed network of observations. The ability to vary the regional atmospheric constraints on the ice-ocean system, and vice versa, is an important advantage and a reason why RCMs complement global models as a way of understanding the functioning and variability of Arctic climate and its interconnectivity with lower latitudes.

At the RCM scale, an intercomparison will be conducted similar to the Arctic Regional Climate Model Intercomparison Project (ARCMIP) based on the SHEBA observations over one year (Tjernström et al. 2005; Inoue et al. 2006; Rinke et al. 2006; Wyser et al. 2008). The objective of this intercomparison will be to assess and document the performance and systematic biases of state-of-the-art RCMs over the Arctic utilizing the detailed MOSAiC measurements and any other data available from contemporary campaigns or operational stations. The MOSAiC observations and process studies will also support future Regional Climate Model Intercomparisons for the Arctic Ocean that include coupled models where complex feedbacks between atmosphere, sea ice, and ocean are interactively simulated (Döscher et al. 2010; Dorn et al. 2012). In previous uncoupled model experiments, uncertainties in prescribed atmospheric forcing may have produced many of the problems in modeled sea ice thickness distributions and impacted the ocean circulation (Proshutinsky et al. 2012). Supported by experiences from process modeling (Section 4.2), RCM inter-comparison and evaluation work is expected to inform the development of better parameterisations for coupled regional climate models.

Evaluation of model results against MOSAiC observations is an integral part of an intercomparison project, and for further development of physical parameterizations, regional climate modeling will play an essential role in MOSAiC. This will also facilitate a better understanding of interactions and teleconnections between the Arctic and mid-latitudes. This requires both detailed observations on the surface exchange and ABL processes in the Arctic (see Section 2.5), and model experiments on the relationships between these local processes, baroclinic instability, and large-scale circulation covering the whole pan-Arctic domain. For example, Rinke et al. (2013) analyzed atmospheric feedbacks in autumn/winter to anomalously low September sea ice cover using an ensemble of simulations with the high-resolution coupled atmosphere-ocean regional model HIRHAM-NAOSIM. They simulated the sea ice evolution during the 60-yr period 1949-2008, and discuss responses to regional sea ice concentration anomalies. This model reproduced important sea ice-atmosphere relationships, particularly the cold-winter-temperature-related feedbacks. This is particularly relevant with respect to possible future model predictability studies on seasonal time scales, which likely require models to reproduce the relevant feedbacks and interactions (e.g., Orsolini et al. 2012). Internally generated climate variability causes significant uncertainty in the simulated circulation changes due to sea ice-atmosphere interactions, and the simulated atmospheric feedback patterns depend strongly on the position and strength of the regional sea ice anomalies and on the analyzed time period.

### 4.4 Large-scale Model Analyses

One aim of MOSAiC is a better understanding of the interplay of ice, atmosphere, and ocean processes in the evolving Arctic climate and how these link with the global climate system. To answer large-scale questions on present and future changes, the most suitable tools are global, coupled Earth System Models (ESMs) that represent the governing processes and their interplay as realistically as possible. State of the art ESMs have problems in the central Arctic, some related to numerical issues such as lack of proper horizontal and vertical resolution, some due to lack of process understanding and representation. A central outcome of MOSAiC is therefore improved large-scale ESMs.

MOSAiC large-scale modelling activities will be an area of active collaboration with the WCRP Polar Climate Prediction Initiative and WWRP Polar Prediction Project. It is important to not only evaluate the model state but to do process-evaluation to determine if the ESMs reproduce observed relationships between variables. The aim of the PPP initiative is to understand the drivers of Arctic sea ice loss and to better predict the rate of ice loss on time scales of hours to seasons, with the help of improved NWP models and GCMs. MOSAiC will be coordinated with the PPP-YOPP (see above) with the intention of MOSAiC observations serving as a test bed for a variety of international YOPP-related modelling activities. Improved knowledge about process descriptions in large-scale models will improve both ESMs and forecast models.

MOSAiC contributions to large-scale modelling activities can be split into four different, central themes: 1) Assessment of model performance against field observations; 2) Improvement of underlying parameterizations of key physical processes; 3) Development, use, and analysis of assimilation techniques that might allow for seasonal and decadal predictions of the evolution of the Arctic climate system; and 4) Usage of Earth System Models to analyze and understand the interplay of Arctic climate system processes and their relationship to the global climate system.

#### *Assessment of model quality*

A major challenge in assessing model simulations of the Arctic climate system against the observed evolution of key variables lies in the substantial internal variability that governs temporal evolution of these variables. Often, this internal variability is so large it can explain the difference between an individual model simulation and reality. An assessment of model quality therefore strongly depends on the assessment of the interplay of different processes that can robustly be determined from observations, as outlined in Section 4.1. Once a model shortcoming has been identified in this way, additional difficulty occurs from the complexity of today's ESMs; modeled processes interact non-linearly across a variety of spatial and temporal scales. Hence, even if a model shortcoming can be identified, it remains a major challenge to pin down the ultimate process or parameterization that is responsible. During MOSAiC, we will address this challenge through simulating individual processes with the hierarchy of models at a variety of length scales, reaching from large-eddy simulations to global scale. Through a direct intercomparison of the resulting simulations both for idealized case studies and for a realistic temporal evolution of external drivers, the key processes that are poorly represented in large-scale models will be identified.

### *Improved description of processes in large-scale models*

The modelling approach of MOSAiC to combine insights gained from models at multiple grid resolutions supports the development of more realistic representations of key processes in large-scale models. The workflow for such improvement will always start with improved insights gained through the observational program. Based on the observations, process models will be developed, tested, and/or improved. Process model results will then be used to develop parameterizations for high-resolution regional models. Based on simulations carried out by these higher resolved regional models, statistical distributions of relevant processes are derived that can be used to upscale the parameterizations to global scale.

A key challenge in this process chain lies in the fact that regional models sometimes use different physical process descriptions than global-scale models. Insights from high-resolution models can therefore not necessarily be directly transfered into a specific global model. To address this issue, an intermediate setup will be used in which a global model will have a spatial resolution in the Arctic that is similar to those of regional models. In this way, the impact of resolution and of largely different model physics can be diminished when moving from regional models to global, large-scale models. This methodology will also assure that simulation results by the high-resolution model domain in the Arctic are not affected by prescribed lateral boundary conditions that are necessary for regional models. Based on the improved representation of large-scale models reached through this process chain, these models will then be used as tools for both fundamental understanding and for better climate projections and predictions.

### *Data assimilation for short-term and medium-term weather predictions*

For weather predictions, assimilation of observational data is crucial. Through such assimilation, the model state is more strongly constrained to the observed trajectory of the system, thereby minimizing the impact of internal variability on short-term climate trends in model simulations. MOSAiC-related modeling activities will employ modern data assimilation techniques used by weather services around the world to bring model simulations in agreement with observed patterns. Such data assimilation will not only allow for the use of models as tools for predicting the future evolution of the Arctic system, but will also allow for new insights into shortcomings in model physics: During assimilation, the degree to which a specific combination of observational data is inconsistent with model physics can be evaluated. This will bring a stronger constraint on model process formulations that are not realistically represented.

Activities supporting data assimilation work relevant for MOSAiC have already been started. Inoue et al. (2013) investigated the impact of radiosonde data from the ice-free Arctic Ocean, obtained by the Japanese R/V Mirai during a cruise in the fall of 2010, on the AFES-LETKF experimental ensemble reanalysis version 2 (ALERA2) dataset. The reanalysis used additional radiosonde data over the ice-free region. Compared with observations, it successfully captured Arctic cyclogenesis along the marginal ice zone, including a tropopause fold. Without the observations, a 5 K cold bias in air temperature was found, suggesting that radiosonde observations over the Arctic Ocean are vital for reproducing tropopause variability.

To further evaluate the impact of additional soundings, the Arctic Research Collaboration for Radiosonde Observing System Experiment (ARCROSE) was conducted as a MOSAiC pilot study, combining intensified radiosonde observations at 3 central Arctic sites (Ny-Ålesund, Tiksi, and the RV Mirai placed at 77.5N, 173W) during a 4-week campaign in September 2013. The additional radiosonde data were assimilated by the Earth Simulator (Observing System Experiment). Emphasis of the analyses was on the Arctic Ocean region where cyclones frequently pass. The higher observation frequency demonstrated clear forecast improvements for reproducing large-scale atmospheric circulations (Inoue et al. 2015; Yamazaki et al. 2015). In fact, observations acquired even far from the Arctic cyclone center affected the prediction of the cyclone (Inoue et al. 2015). As the wind-driven sea ice drift is crucial to determine sea ice conditions, improved wind fields via assimilation of additional radiosonde data also supports improved sea ice forecasts.

Overall, these assimilation studies demonstrated that high-temporal radiosonde observations over the Arctic Ocean and at coastal Arctic sites can help reduce uncertainty in reanalyses and numerical weather predictions throughout the northern half of the Northern Hemisphere for weeks afterwards. Furthermore, increased upper-air observations are expected to improve the prediction and reproduction of individual disturbances and climatic fields both within the Arctic region and at lower latitudes (Inoue et al., 2013). The MOSAiC drift offers the unique opportunity to obtain these additional upper-air measurements over the Arctic Ocean, and to further evaluate their impact on forecast systems through a complete annual cycle. The combination of radiosonde profiles from the MOSAiC platform, with potential increased radiosonde launch frequency at Arctic coastal sites during this time, will provide high-resolution upper-air observations to be included into existing data assimilation systems.

*Earth-System Model simulations to improve understanding of the Arctic Climate System*

MOSAiC activities will contribute to a set of coupled Earth-System-Models that best represent the physical and biogeochemical cycles that govern the evolution of the Arctic climate system. These improved models will then be used as tools in identifying drivers of observed changes and large-scale global linkages related to Arctic change. In particular, such coupled Earth-System-Models will be key in better understanding the underlying mechanisms of the observed Arctic Amplification. Whereas this amplification is typically linked to the ice-albedo feedback, a recent study strongly points towards the atmospheric water-vapor feedback as being influential, both in observations and model simulations (Mauritsen et al. 2011). Given the likely improvement of the representation of the atmospheric water cycle that will result from the MOSAiC initiative, models incorporating such improvements will help to shed more light on this long-standing, fundamental question.

Large-scale model simulations are also critical to better understand the interaction of changes in the Arctic climate system with observed changes at lower latitudes. Coupled model studies are needed to evaluate, for example, the effects of sea ice loss and the resulting enhanced surface heat fluxes on Northern Hemisphere synoptic circulation patterns. This focus on Arctic linkages to hemispheric and global teleconnection patterns we be explored in coordination with the PPP – YOPP activity.

# 5. TOWARDS IMPLEMENTATION

This Science Plan lays out the scientific vision and context for MOSAiC. To successfully implement this interactive, inter-disciplinary and coupled-system science plan will require strong leadership and coordination of international and interagency science, infrastructure, and funding contributions. This process requires a well-designed Implementation Plan that outlines: specific measurement requirements, a scheme for deploying observational assets in the field, drift path considerations, logistical plans for re-supply and crew rotations, allocation of field personnel, operational modeling and forecasting, safety protocols, and education and outreach activities. The plan must outline a strong data management plan that will preserve the MOSAiC legacy and facilitate its use by research and stakeholder communities.

Support for implementation planning has been provided by the International Arctic Science Committee (IASC) via the International Conference on Arctic Research Planning (ICARP III) process. An international team of scientists has contributed to the Implementation planning process and a first draft of the MOSAiC Scientific Implementation Plan will be released in March 2016. As part of this planning process, the Alfred Wegener Institute has identified Markus Rex as the MOSAiC coordinator.

## CONTRIBUTORS

This document has been written by a MOSAiC Science Plan writing team that was identified to represent different disciplinary and national perspectives. Many of the initial science ideas were developed through workshops held in Potsdam, Germany (26-27 September 2011) and Boulder, Colorado (27-29 June 2012). A science plan writing workshop was also held in Potsdam (29-30 May 2013) to refine the focus and plan. The science plan writing team has been responsible for the primary drafting of all sections in the document. Numerous other contributions have been made via open community feedback, comments, and input into the Plan. Primary editorial oversight has been provided by Matthew Shupe, University of Colorado.

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*The Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC) is a key international flagship initiative under the auspices of the International Arctic Science Committee (IASC). The main aim of MOSAiC is to improve our understanding of the functioning of the Arctic coupled system with a complex interplay between processes in the atmosphere, ocean, sea ice, and ecosystem coupled through biogeochemical interactions. The main objective of MOSAiC is to develop a better understanding of these important coupled-system processes so they can be more accurately represented in regional- and global-scale weather- and climate models. Observations covering a full annual cycle over the Arctic Ocean of many critical parameters such as cloud properties, surface energy fluxes, atmospheric aerosols, small-scale sea-ice and oceanic processes, biological feedbacks with the sea-ice ice and ocean, and others have never been made in the central Arctic in all seasons, and certainly not in a coupled system fashion. The main scientific goals focus on data assimilation for numerical weather prediction models, improved sea ice forecasts and climate models, ground truth for satellite remote sensing, energy budget and fluxes through interfaces, sources, sinks and cycles of chemical species, boundary layer processes, habitat conditions and primary productivity and stakeholder services. In view of these important expected outcomes and the international collaborative character of MOSAiC IASC endorses this initiative with great enthusiasm.*

***Susan Barr, IASC President***