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Special Section:

Forum for Arctic Modeling and Observing Synthesis (FAMOS): Results and Synthesis of Coordinated Experiments

Key Points:

- This is an introduction to the JGR FAMOS issue summarizing 3 year study results
- Coordinated experiments improved models and investigated ocean, ice, and ecosystem processes
- FAMOS collaborations are an important and unique component of present-day Arctic studies

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Forum for Arctic Modeling and Observational Synthesis (FAMOS): Past, current, and future activities

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Abstract The overall goal of the Forum for Arctic Modeling and Observing Synthesis (FAMOS) community activities reported in this special issue is to enhance understanding of processes and mechanisms driving Arctic Ocean marine and sea ice changes, and the consequences of those changes especially in biogeochemical and ecosystem studies. Major 2013–2015 FAMOS accomplishments to date are: identification of consistent errors across Arctic regional models; approaches to reduce these errors, and recommendations for the most effective coupled sea ice-ocean models for use in fully coupled regional and global climate models. 2013–2015 FAMOS coordinated analyses include many process studies, using models together with observations to investigate: dynamics and mechanisms responsible for drift, deformation and thermodynamics of sea ice; pathways and mechanisms driving variability of the Atlantic, Pacific and river waters in the Arctic Ocean; processes of freshwater accumulation and release in the Beaufort Gyre; the fate of melt water from Greenland; characteristics of ocean eddies; biogeochemistry and ecosystem processes and change, climate variability, and predictability. Future FAMOS collaborations will focus on employing models and conducting observations at high and very high spatial and temporal resolution to investigate the role of subgrid-scale processes in regional Arctic Ocean and coupled ice-ocean and atmosphere-ice-ocean models.

1. Introduction

The rapidly changing Arctic climate [e.g., *Proshutinsky et al.*, 2015] provides an exceptional opportunity to document Arctic change, analyze underlying processes and the consequences of Arctic variability, and ultimately understand the mechanisms driving Arctic transitions under the influence of global warming that will allow for more accurate climate prediction. Undeniably, it is difficult to describe and understand changing sea-ice, ocean, and ecosystem conditions based on the sparse observations alone. Modeling, constrained by available observations, is clearly required on many different levels—from simplified and idealized process models to regional and pan-Arctic fully coupled atmosphere-ice-ocean models. The Arctic is particularly challenging in this regard, owing to the unprecedented complexity of all processes influenced by sea ice conditions, and also to the key role that processes operating on very small scales play in the basin-scale mean hydrographic conditions and circulation. For example, mesoscale ocean eddies ($\sim$10 km radius) that are not generally resolved by most models are commonly found in the Arctic Ocean, and are known to transport heat and salt anomalies between the shelf and interior basins, and enhance local mixing. Small-scale turbulent mixing processes are also essential for the large-scale Arctic circulation and transport of heat and salt, yet the location, strength, and mechanisms that drive diapycnal mixing in the Arctic are not well understood. One strategy to tackle this problem is the combined use of both high-resolution process-oriented models, as well as lower-resolution basin-scale models, where the former provides parameterizations for the latter.

On the other hand, it is problematic to use models in a predictive capacity without proper knowledge of model errors and uncertainties. For example, small errors in ice parameters or atmospheric forcing can translate into significant errors in fluxes to the ocean and thus ocean state parameters. For this reason, Model Intercomparison Projects (MIPs) that include model validation based on observations are essential. Presently, there are insufficient observational data available for model initialization, forcing, validation, and

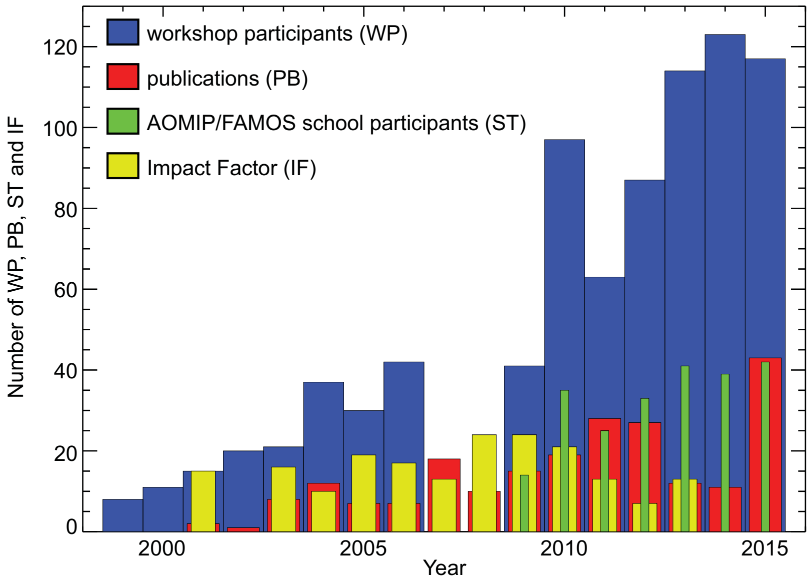

Figure 1. Number of AOMIP/FAMOS meeting participants (blue); number of publications per year (red); number of school students (green); and Impact Factor (IF) calculated as the ratio of number of citations for papers published in a given year to number of papers in that year (yellow). IF is calculated only for papers published in JGR, GRL, and EOS, and it is not calculated after 2013 due to insufficient information on the number of citations.

assimilation, and a comprehensive Arctic observational network is urgently needed to satisfy the needs of both the observational and modeling communities.

It is well known that global climate models often have large errors relative to observations in their Arctic domains. Regional coupled atmosphere-ice-ocean Arctic models or ice-ocean models with high spatial resolution are generally more accurate than global models, but frequently show striking differences in MIP studies. In this sense, it is clear that a set of improvements is vital for all types of Arctic models, e.g., better initial and boundary conditions, establishment of initialization techniques for seasonal and decadal prediction systems, and advanced forcing and parameterizations of unresolved processes (e.g., ocean mixing, ocean-ice-atmosphere interactions). One important outcome of the activities outlined here is a better understanding of the strengths and weaknesses of different models or classes of models, and the sensitivity of model predictions to key processes—information that can then be used to assess future predictions and to guide fully coupled global and regional climate model development.

The studies presented in this FAMOS special issue contribute new understanding and progress on the problems outlined above. The next section of this introductory paper provides a historical overview of the project (in the years that laid the groundwork for its latest phases), including objectives and key findings (see Tables in Appendix and Figure 1 for FAMOS statistics). Section 3 explores, and sets in context, the major results of papers published in this special issue. The final section outlines future FAMOS plans for 2017–2019.

2. From AOMIP to FAMOS

FAMOS was organized in 2013 as a logical continuation of its predecessor: AOMIP (Arctic Ocean Model Intercomparison Project, 1999–2012). Below we report on the historical development of AOMIP and accomplishments of the AOMIP team in order to motivate the goals, approach, and organization of FAMOS.

2.1. AOMIP-1: 1999–2007

AOMIP was established in 1999, and a total of five publications analyze and summarize results from its first phase (AOMIP-1) [*Proshutinsky et al.*, 2001a, 2001b, 2005; *Proshutinsky and Kowalik*, 2007; *Proshutinsky et al.*, 2008a, 2008b]. During this first phase, studies revealed striking, previously unknown differences among Arctic models (Table A1). Based on model validations against observational data, AOMIP teams identified a set of parameters and processes where physical understanding was lacking, and/or numerical improvements were needed (Table A2). It was found, for example, that six out of the eight AOMIP coupled ice-ocean models that participated in the first coordinated experiment exhibited unrealistically large drifts from mean climatological salinity [*Steele et al*., 2001]. Further, it was found that only three of the models realistically captured the cyclonic (counterclockwise) flow of Atlantic Water (AW) around the continental slopes of the Arctic Ocean, while others simulated an exact opposite (anticyclonic) flow. These results only became apparent when all modelers came together and openly compared their results in a meeting setting; following this, several teams met to diagnose differences and develop solutions. It was concluded that the unrealistic anticyclonic AW flow could be reversed in a model by reducing mixing [*Zhang and Steele*, 2007; *Golubeva and Platov*, 2007] to levels that were significantly lower than those typically found in the rest of the World Ocean, but were in fact consistent with the limited observational database on Arctic mixing. The reduction of ocean mixing had the further consequence of eliminating the need for unphysical climate restoring, a numerical adjustment that had been required previously to limit unrealistic drift away from climatological observations. These findings have been frequently cited in recent papers focused on the future potential for increased Arctic Ocean mixing in response to decreasing sea ice cover [e.g., *Rainville and Woodgate*, 2009]. In addition, these issues discussed at project meetings led other AOMIP participants to clarify the basic physics of AW circulation [*Karcher et al*., 2007; *Yang*, 2005; *Karcher et al*., 2012]. Additional themes of AOMIP study during this period are provided in Table A3.

In the years 1999–2007, 11 AOMIP meetings were held, and more than 50 peer-reviewed papers were published, with more than 80 talks and posters presented. AOMIP meetings took place in different locations (Naval Postgraduate School, University of Washington, Woods Hole Oceanographic Institution, Geophysical Fluid Dynamics Laboratory, McGill University, and University of Hawaii) in order to involve early-career Arctic researchers and students from these institutions and maximize engagement of the Arctic community.

The AOMIP coordinated community approach has been shown to be the most effective way to assess the degree of uncertainty in model results and ascertain key limitations and problems in models that are presently used in a predictive capacity. The most significant AOMIP-1 contributions during this phase were identification and attribution of model discrepancies and errors, and recommendations for improvements to existing regional coupled ice-ocean models and GCMs by implementing new physics and parameterizations. In addition, a set of process studies completed in this phase contributed to understanding of ocean circulation, sea level variability, sea ice characteristics, and the role of tides in sea ice and ocean processes.

2.2. AOMIP-2: 2008–2012

In the second phase of AOMIP, several new thrusts were implemented, namely: strengthened collaboration between modelers and observationalists; inclusion of a wider representation of Arctic marine interests; and an emphasis on teaching and inclusion of early-career scientists and scientists new to the area of Arctic research. A special JGR issue "Arctic Ocean Investigation Employing AOMIP-2 Models" (*Kuzmina et al.* [2011], *Jahn et al.* [2012], *Popova et al.* [2012], *Martensson et al.* [2012], *Nguyen et al.* [2011], *Holloway et al.* [2011], *Houssais and Herbaut* [2011], *Timmermans et al.* [2011], *Gao et al.* [2011], *Wang et al.* [2011], *Rampal et al.* [2011], *Johnson et al.* [2012], *Karcher et al.* [2012], *Dupont et al.* [2012], *McGeehan and Maslowski* [2012], *Kwok* [2011], *Rudels* [2011], *Schweiger et al.* [2011]) provides a sample of significant AOMIP work during this period; this is in addition to the more than 60 other papers published by AOMIP participants. Examples of this collaborative work are provided in Table 4 (see Appendix). In the years 2008–2012, five AOMIP meetings were held (yearly) at Woods Hole Oceanographic Institution.

Data assimilation was an additional new thrust during this period, wherein experts in this field from the Massachusetts Institute of Technology (MIT), University of Alaska Fairbanks (UAF) and elsewhere contributed several key studies [e.g., *Panteleev et al*., 2010; *Fenty*, 2010; *Heimbach*, 2008; *Kauker et al*., 2009]. The subject of ecosystem modeling was also introduced, involving experts from United Kingdom National Oceanographic Center, UAF, New York University and elsewhere. An example of their results is the finding that modeled surface mixed layers were generally too deep compared to observations, which affects nutrient supply and primary productivity [e.g., *Popova et al*., 2010, 2012].

2.3. FAMOS-1: 2013–2016

FAMOS (www.whoi.edu/projects/famos) is a logical continuation of AOMIP, with an even stronger emphasis on the synthesis of model and observational results. In its first phase, FAMOS-1, six scientific teams were organized for coordinated studies of Atlantic water circulation, freshwater changes in the Arctic Ocean, sea ice drift, ice

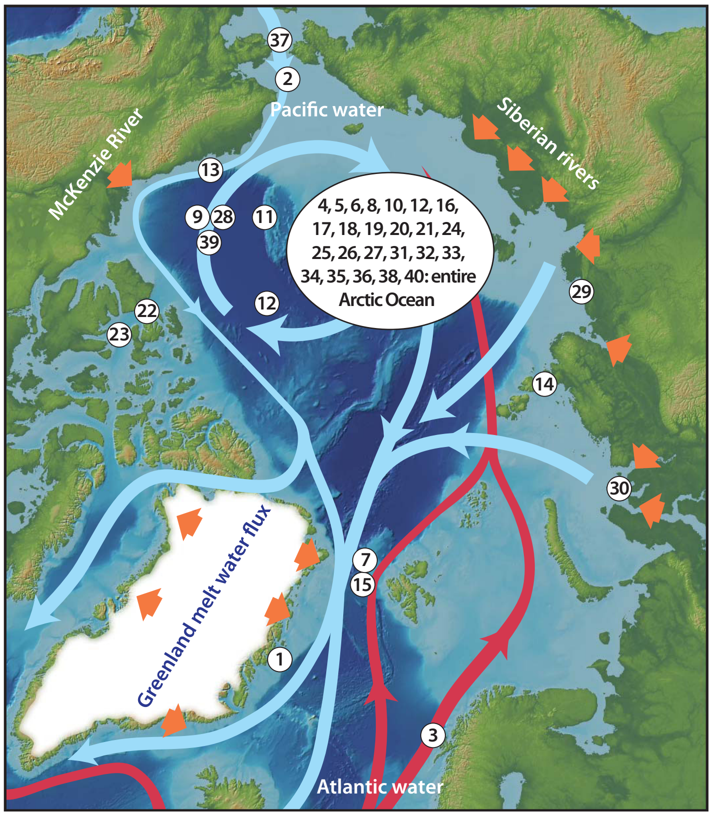

Figure 2. Schematic showing FAMOS publications in this special issue by geographic focus. Large arrows are an approximate schematic indication of the major pathways of Pacific waters and fresh surface waters (blue), Atlantic waters (red), and melt water flux from Greenland and major regions of river runoff (orange). Numbers in circles indicate papers in this special issue as follows: 1—*Dukhovskoy et al.* [2016], 2—*Aksenov et al.* [2016], 3—*Chafik et al.* [2015], 4—*Nummelin et al.* [2016]; 5—*Stroh et al.* [2015], 6—*Luneva et al.* [2015], 7—*Granskog et al.* [2015], 8—*Ding et al.* [2016], 9—*Yang et al.* [2016], 10—*Pemberton and Nilsson* [2016], 11—*Zhao and Timmermans* [2015], 12—*Bebieva and Timmermans* [2016], 13—*Jackson et al.* [2015], 14—*Janout et al.* [2015], 15—*Marnela et al.* [2016], 16—*Webster et al.* [2016], 17—*Roy et al.* [2015], 18—*Abraham et al.* [2015], 19—*Martin et al.* [2014], 20—*Martin et al.* [2016], 21—*Rabatel et al.* [2015], 22—*Hata and Trembley* [2015a], 23—*Hata and Trembley* [2015b], 24—*Steele and Ermold* [2015], 25—*Schweiger and Zhang* [2015], 26—*Hebert et al.* [2015], 27—*Close et al.* [2015], 28—*Petty et al.* [2016], 29—*Selyuzhenok et al.* [2015], 30—*Olason* [2016], 31—*Dukhovskoy et al.* [2015], 32—*Yool et al.* [2015], 33—*Lawrence et al.* [2015], 34—*Jin et al.* [2016], 35—*Steiner et al.* [2016], 36—*Lee et al.* [2015], 37—*Panteleev et al.* [2016], 38—B. Rudels, Arctic Ocean Stability: The effects of local cooling, oceanic heat transport, freshwater input and sea ice melt with special emphasis on the Nansen Basin, J. Geophys. Res. (submitted manuscript, 2016), 39—*Howel et al.* [2016], 40—*Lemieux et al.* [2015].

ridging, and other ice-related processes (including fast ice studies), and ecosystem processes. More than 60 papers were published, including 39 in this JGR special issue (Figures 1 and 2). Table A5 summarizes the major themes of all FAMOS-1 publications in 2013–2016.

3. Toward Better Understanding of the Arctic Ice, Ocean, and Ecosystem Processes

In this section, we summarize the major results of publications presented in this special issue covering physical, biogeochemical, and ecosystem aspects of Arctic change. Some papers have a regional focus, while others consider the entire Arctic region (Figure 2). By way of a general orientation, we provide only brief information on each paper, and set the studies in context with each other. The reader is encouraged to pursue the details within the papers and consider the best approach and topics for future studies.

3.1. Sea Ice

One of the most important scientific priorities in the study of Arctic change is the understanding of the observed sea ice extent and thickness reduction, and the acceleration of sea ice drift. In this section, we describe results of FAMOS sea ice research, where publications can be subdivided as follows: papers analyzing sea ice melt pond and snow properties, research focusing on pack ice dynamics and thermodynamics, fast ice generation and break-up conditions, and sea ice prediction.

3.1.1. Sea Ice Melt-Ponds and Snow Conditions

Melt ponds and snow conditions on sea ice are key elements of Arctic models for their influence on surface radiative fluxes, sea ice growth and decay, and specifying albedo parameters. In this issue, *Webster et al.* [2016] analyzed the seasonal evolution of melt ponds on Arctic sea ice. Both satellite imagery and in situ observations were used to analyze melt pond evolution on first year and multiyear pack ice. The authors found that melt ponds formed 3 weeks earlier on multiyear ice than they did on first year ice, which they explained in terms of different snow conditions on the first and multiyear ice floes. In a related study in this issue, *Abraham et al.* [2015] employed an idealized model to show how the subgrid-scale snow thickness distribution influences light and heat fluxes through sea ice. Of some significance is that their results can explain differences between observed thermal conductivity of snow and values typically used in models.

3.1.2. Pack Ice Dynamics

"Wind blows – ice goes"—this traditional rule of thumb is now more appropriate than ever to describe the sea-ice response to wind driving. As sea ice thickness and concentration continue to decline, so too do internal ice stresses. On the other hand, sea ice deformation and ridging play an increasing role which, for example, can result in the convergence and accumulation of sea ice against coastlines [*Kwok and Cunningham*, 2015; not in this issue].

In this special issue, two papers explore how changing sea ice conditions (which impact ice-ocean drag) influence energy transfer from the wind to the ocean [*Martin et al*., 2014, 2016]. These authors introduce an interesting hypothesis, supported by model simulations, that there exists some optimal sea ice concentration that yields maximum energy transfer from the wind to the ocean. This may have, for example, important implications for freshwater content changes in the Beaufort Gyre region.

The study by *Martin et al*. [2016] was corroborated by another study in this issue by *Roy et al*. [2015]. These authors showed that, in addition to sea ice roughness conditions, the parameters characterizing atmospheric and oceanic boundary layers also have an essential role in influencing air-ice and ice-ocean drag coefficients. *Roy et al*. [2015] investigated, for example, the dependence of Beaufort Gyre freshwater accumulation on sea ice and wind conditions, including ice thickness and drag parameters. It was found, for example that improved sea ice drift parameters resulted in reduction of sea ice accumulation in the Beaufort Sea, correcting a typical ice thickness bias.

Martin et al. [2014, 2016] and *Roy et al*. [2015] acknowledged that there remain many open questions related to the treatment of the atmosphere-ice-ocean boundary layers, and that new observations and additional modeling and analytical studies are needed. Future modeling and observations with higher spatial and temporal resolution will be a step in this direction (discussed further in section 4, where future FAMOS plans are outlined).

This issue also includes the study of *Rabatel et al*. [2015], who combined numerical and laboratory experiments to investigate the dynamics of an assembly of rigid ice floes with a simple granular rheology, influenced by atmospheric and oceanic drag. This study is important for modeling of sea ice floe interactions in high-resolution models with horizontal scales of ice floes less than 10 km^2; at these scales, the discontinuous nature of sea ice cover cannot be neglected when considering sea ice mechanics and kinematics.

3.1.3. Fast Ice Formation and Break-Up: Observations and Models

Land-fast (briefly, "fast") ice forms along the coast, remaining attached there for long periods and in some cases, through the entire winter. It can occupy up to 40% of the area of some Arctic marginal seas, protecting the ocean from wind stress, and damping tidal motion and winter storm surges. Fast ice influences the distribution of river runoff, and is associated with enhanced wind mixing at its outer boundary. Despite efforts to include fast ice formation and decay in idealized and regional 3-D models [e.g., *Konig-Beatty and Holland*, 2010], there has been no successful implementation of fast-ice models into realistic Arctic Ocean simulations.

Three papers in this issue focus on regional sea ice processes and fast ice modeling in the Arctic marginal seas. *Selyuzhenok et al*. [2015] investigated the seasonal and interannual variability of fast ice extent in the Laptev Sea over 14 years following 1999. Their analysis showed significant sensitivity of fast ice to atmospheric thermal conditions (expressed, for example in freezing degree days). Notably, wind conditions also play an important role in the initial stages of fast ice formation, where onshore winds result in earlier fast ice formation due to advection of pack ice toward the shore. This paper provides many details about regional features of fast ice in the Laptev Sea which can be used for the validation of regional Arctic models.

A second paper, by *Olason* [2016], deals with Kara Sea fast ice. The paper is particularly useful for its comprehensive introduction to fast ice conditions in the Kara Sea, and its description of regional fast ice models. A main assumption underlying Olason's approach is that Kara Sea fast ice forms via static arching, with the bases of the arches resting on a chain of offshore islands. Even in the face of complicating factors, such as significant river runoff, irregular bathymetry, and strong cyclone activity, the model generally reproduces the observed fast ice extent reasonably well, and these studies provide some confidence that our ability to model and predict fast ice is improving.

The third fast-ice paper in this special issue is by *Lemieux et al*. [2015], who discuss a simplified approach to parameterize fast ice via the introduction of grounded ice keels. Their approach leads to reasonable representations of fast ice areas of the Siberian and Beaufort Seas, although in the Kara Sea region, the absence of simulated ice arches [cf. *Olason*, 2016] resulted in the underestimation of fast ice area.

Also pertaining to fast ice, two papers in this issue analyze internal stresses in "landlocked" winter sea ice in the straits of the Canadian Archipelago [*Hata and Tremblay*, 2015a, 2015b]. The authors investigated internal thermal stresses in landlocked ice floes using observations and modeling. Their major finding is that the anisotropic behavior of thermal stresses is related to external factors, such as land confinement geometry and the influence of surface current direction on the ice crystal orientation during ice formation. These results shed new light on the structure and formation of fast ice and its break-up.

3.1.4. Predictability of Sea Ice Conditions

Several papers in this special issue focus on the analysis and prediction of sea ice conditions at seasonal and longer time scales. *Steele and Ermold* [2015] identified a phenomenon in which the retreat of seasonal sea ice slows down for a period of up to 10 days in certain regions. They refer to this effect as "loitering," which may arise by interactions between a number of dynamical and thermodynamical atmospheric, ice, and ocean factors, described in detail in the paper. It is interesting that over the past 25 years the total area affected by loitering during the retreat season has remained the same. This stability in sea-ice retreat patterns could be valuable in synoptic sea-ice forecasts and, as the authors speculate, the loitering may have profound effects on both physical and biological conditions at the ice edge zone.

The accuracy of sea ice drift prediction on subdaily to 9 day timescales was analyzed by *Schweiger and Zhang* [2015] in this issue; their study is based on 2014 summer operational forecasts employing the Marginal Ice Zone Modeling and Assimilation System [MIZMAS: http://psc.apl.uw.edu/research/projects/mizmas/]. Their goal was to evaluate the feasibility of short-term forecasting for field operations in the Arctic. The major obstacle to accurate forecasts, which is corroborated by other studies [see also *Hebert et al*., 2015 in this issue], is that errors in atmospheric forcing dominate all other effects. The authors note that the complex MIZMAS system does not yield significantly better results than a simple free ice drift model, although they point out that the dynamic MIZMAS may be better in certain sea-ice conditions. We note that sea ice conditions in the summer MIZ are effectively free drift; at higher ice concentrations, MIZMAS may be an improvement over a simple free drift model, although the issue of errors in atmospheric forcing remains.

Further on the topic of sea-ice forecasting, *Hebert et al*. [2015] assessed the accuracy of sea ice concentration/drift forecasts (up to 7 days in advance) using the U.S. Navy operational Arctic sea ice forecasting system (ACNFS) for the period February 2014 to June 2015. They focus their assessment of model skill on areas where the observed sea ice concentration change exceeded $\pm5\%$ over a 5 day period; a logical approach given that predictions of sea ice concentration in regions of the central Arctic, where ice cover is about 100% year-round, will be consistently excellent. It is found that ACNFS forecasts are skillful compared to assuming a persistent ice state, especially beyond 24 h and particular skillful compared to a climatologic state for forecasts up to 102 h.

One question for the sea ice modeling community, and one underlying theme in FAMOS studies, is how to objectively evaluate the accuracy of model predictions. There are numerous metrics that are single numbers (e.g., ice volume, ice area, ice extent) or 2-D/3-D shapes of sea ice mass horizontal and vertical distributions. As a FAMOS workshop exercise to stimulate discussion and interest, participants are requested to contribute their own metrics (e.g., Figure 3 shows 56 minimum sea ice extent representations drawn by FAMOS participants). To consider how this might be used to develop an effective sea-ice metric, *Dukhovskoy et al*. [2015] analyzed these individual guesses against the observed extent distribution using five different methods. Among them the Modified Hausdorff Distance (MHD) method showed the best results, and provided a metric that included the detailed geometry of the predicted ice edge, in addition to standard information such as total extent. This can be employed for any other sea ice characteristic (e.g., thickness, melt-pond distribution, drift speed), and can also be applied for validation of simulated fields wherever both shape and distribution are of importance.

Motivated by the need to better understand causes, predictability and periodicity of sea ice conditions on long timescales, *Close et al*. [2015] investigated the timing of the onset of the recent rapid loss in sea ice. They concluded that accelerated sea ice loss in the Arctic Ocean's Atlantic sector began in 2003, while in the Pacific sector, the transition to accelerated loss of sea ice began as early as 1992. Their findings are a clear demonstration that rates of basin-scale sea ice decline can be masked significantly by regional conditions, which must be taken into account for better interpretation of the observations and predictions.

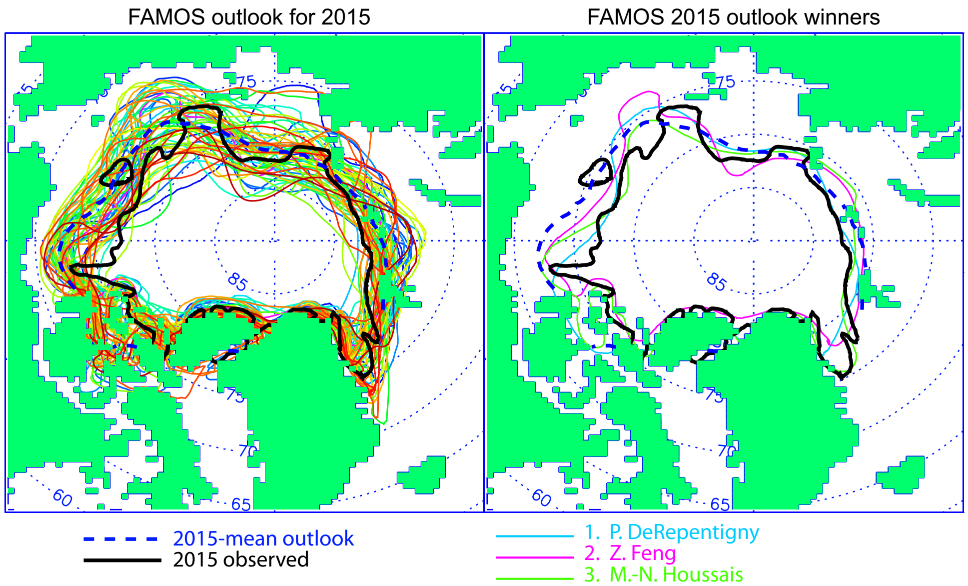

Figure 3. (left) 2015 sea ice minimum extents predicted (typically, simply guessed) by 56 participants of the Third FAMOS meeting in 2014. (right) Best outlook results based on the analysis by *Dukhovskoy et al.* [2015]. The observed sea-ice minimum extent is also shown.

3.2. Ocean Freshwater and Heat Dynamics

Investigations of freshwater and heat content in the Arctic Ocean are important elements of AOMIP and FAMOS studies. Coordinated numerical (see Tables A3 and A4) and observational experiments (see special issue "Beaufort Gyre Climate System Exploration Studies" in Journal of Geophysical Research Oceans, *114* C00A08, 2009) have been conducted since the start of AOMIP in 1999.

In this special issue, three papers address these topics, with particular attention on future change. *Ding et al.* [2016] analyzed 14 CMIP5 coupled simulations to examine mechanisms regulating seasonal variability of ocean freshwater and heat. One of their key findings relates to how sea ice mediates the coupling between ocean heat and salt budgets, which, while intuitive, had not been specifically diagnosed in CMIP5 models before; strong seasonal heating reduces sea ice volume and strengthens the halocline stratification, which further strengthens warming and decreases sea ice (the feedback is also seen in reverse).

The role of freshwater on the central Arctic Ocean stratification is considered in two publications in this issue [*Nummelin et al.*, 2016; *Pemberton and Nilsson*, 2016]. Both studies begin with the assumption that increased atmospheric freshwater flux to the Arctic Ocean and its hydrologic catchment basins, due to intensification of the global hydrological cycle, will result in higher river runoff and precipitation at polar latitudes. *Nummelin et al.* [2015] employed the global (1° grid resolution) coupled ocean-sea ice component of the Norwegian Earth System Model (NorESM) [*Bentsen et al.*, 2013]. In addition to climatological atmospheric forcing, they forced the model with different volumes of river runoff. They find that increased river runoff leads to a strengthening of the central Arctic Ocean stratification and a warming of the halocline and Atlantic Water layers. Further, excess fresh water accumulates in the Eurasian Basin, resulting in local sea level rise and a reduction of water exchange between the Arctic Ocean and the North Pacific and North Atlantic Oceans.

Likewise to understand changes in Arctic Ocean stratification under different future scenarios of river runoff and precipitation, *Pemberton and Nilsson* [2016] in this issue used the MIT Arctic regional coupled ice-ocean-circulation model (in the configuration designed *by Nguyen et al.* [2011, 2012]) with horizontal resolution of 18 km to conduct several freshwater sensitivity experiments. Similar to the results of *Nummelin et al.* [2016], they found that the major changes under increased freshwater relate to the cold halocline and the Atlantic water layer. One intriguing finding is that under an increased freshwater supply, the Beaufort Gyre weakens and there is increased freshwater exported through Fram Strait. At the same time, freshwater flux through the Canadian Arctic Archipelago decreases by almost the same amount. Many unresolved processes (e.g., narrow fresh coastal flows) are common to both studies [*Pemberton and Nilsson*, 2016; *Nummelin et al*., 2015] and merit further investigation in future FAMOS initiatives.

One final paper that can be included under this theme is the study in this issue by *Stroh et al*. [2015] in which satellite sea surface temperature data and model simulated sea surface salinities (from different hydrographic products) were validated against Ice-Tethered Profiler (ITP) data, and CTD/XCTD in situ observations from 2006 to 2013. The results of this study are important not only for assessing model uncertainties, but also for statistically robust analyses of seasonal and interannual Arctic change.

3.3. Ocean Circulation

There are many open questions on the fundamental circulation, dynamics, and water-mass exchanges in the Arctic Ocean. For example, the exact pathways (and their variability) of Pacific water masses (at depths around 50–200 m in the Canada Basin) are not well constrained by observations. The circulation and modification of Atlantic waters (at core depths of 200–500 m) around the Arctic basin are also poorly known and understood. A key recurring question in Arctic climate studies, for example, pertains to how and where Pacific and Atlantic water heat influence climate and sea ice conditions.

Fundamental ocean circulation questions are explored in an idealized Beaufort Gyre (BG) dynamics study in this issue by *Yang et al*. [2016]. This is a continuation of *Yang's* AOMIP/FAMOS-inspired work [*Yang*, 2006, 2009] focusing on the theoretical underpinning and balance of forces that give rise to a stable Beaufort Gyre. *Yang et al*. [2016]'s analysis of the vorticity budget shows that modeled eddies play a critical stabilizing role in BG dynamics. Their results corroborate those of *Manucharyan and Spall* [2016] (not in this issue) who show that the role of eddies have been underestimated in previous studies of BG dynamics [*Proshutinsky et al*., 2002, 2009] based only on changing wind stresses and sea ice parameters.

Pacific water pathways in the Beaufort Gyre and beyond are investigated by *Aksenov et al*. [2016] in this issue. This FAMOS team used results from four regional Arctic models and two global Ocean General Circulation Models (OGCMs) to identify pathways of Pacific water from tracers released in the Bering Strait region. Their results clearly demonstrated that higher-resolution models perform better than low resolution models in reproducing the most realistic flows. In addition to standard parameters, such as the choice of mixing and advection schemes, these authors point out that proper treatment of the oceanic bottom boundary layer is also crucial to accurately model Pacific water circulation patterns.

Also in this issue, *Dukhovskoy et al*. [2016] used a similar tracer approach to investigate pathways of Greenland melt water in the subarctic regions of the North Atlantic. Three groups (from Florida State University, USA; University of Alberta, Canada; and the Institute of Computational Mathematics and Mathematical Geophysics, Russia) ran coupled ocean-ice models with passive tracers released at Greenland meltwater outlets. While results showed general agreement, with tracers following circulation patterns from Greenland to the North Atlantic and via the North Atlantic Current to the Nordic Seas, large differences among models solutions were found in convective regions of the Labrador and Nordic Seas. The authors attribute this to differing eddy resolving capability among models, similar to conclusions of *Aksenov et al*. [2016]. The FAMOS team participating in the *Dukhovskoy et al*. [2016] study consisted of observationalists as well as modelers, which contributed to an entirely integrated analysis of meltwater transport.

Two papers [*Chafik et al*., 2015; *Janout et al*., 2015] in this special issue explore water transport and modification in boundary regions of the Arctic Ocean. *Chafik et al*. [2015] used satellite altimetry, hydrography, and atmospheric data to jointly calculate and analyze variability of the Atlantic water flow through the Nordic Seas at monthly to interannual time scales. *Janout et al*. [2015] conducted numerical experiments using the 3 km resolution NEMO model (the same model as used by *Aksenov et al.'s* [2016] study of Pacific water pathways) to investigate water exchange between the Kara and Laptev Seas via Vilkitsky Strait, the main passage for Kara Sea river runoff. The authors also present a set of rare observations from the region, which is characterized by complex hydrography and sea ice conditions, with fast ice modulating circulation and limiting air-ice-ocean interactions. Results of these studies provide key constraints on circulation at the margins of the Arctic system.

Finally on the topic of ocean circulation, *Panteleev et al*. [2016] present a comprehensive study in this issue of the Bering Sea circulation; their study is based on the Four-Dimensional Variational Data Assimilation (4-DVAR) technique integrated with satellite sea-surface temperature and sea-surface height data, plus extensive in situ mooring and hydrographic station observations. Specifically, the Bering Strait water transport anomalies for two wind forcing events were scrutinized using Lagrangian analysis of water particles. During one of these cases, a 28 day duration reversal of the flow from the Chukchi to the Bering Sea was successfully reproduced. Their study provides a basis for regional studies of Bering Sea ocean physics and biology which require knowledge of water mass transformation, mixing, and advection.

3.4. Mixing and Eddies

Process studies related to ocean mixing and stirring, regional water-mass transport and modification, and mesoscale eddy generation continue to be an important theme of FAMOS. This issue includes studies on ocean tidal and double-diffusive mixing, mesoscale eddy processes, and shelf-basin exchange. *Luneva et al*. [2015] find that tides result in enhanced mixing, leading to higher ocean-to-ice heat fluxes, as well as reduced halocline stratifications. This is the first Arctic-wide study that explicitly compares numerical simulations with and without tides. In an earlier study, *Holloway and Proshutinsky* [2007] assessed the role of tides based on a parameterization of tidal mixing in their coupled ice-ocean model. *Luneva et al*.'s major conclusion is that the presence of tides results in 15% less sea ice over the final decade of their 30 year simulation.

Elevated mixing due to tides has been invoked to explain the observed heat-content evolution of the Atlantic Water layer at the basin margins [e.g., *Rippeth et al*., 2015; not in this issue]. Although double-diffusive mixing processes are generally observed in the Atlantic Water layer across the basin, double diffusion is associated with low mixing levels, and small ocean heat fluxes. There are situations, however, when turbulence and double diffusion operate in the same setting; a mesoscale eddy provides just such a setting. In this issue, *Bebieva and Timmermans* [2016] analyze observations of an Atlantic Water eddy to conclude that the combination of both double-diffusive and turbulent fluxes can lead to rapid mixing of Atlantic Water heat, including downward (in addition to upward) heat fluxes. This provides an observational framework for future FAMOS studies to examine the net effect of such processes for better assessment of Atlantic Water heat transport in noneddy-resolving models.

While *Bebieva and Timmermans* [2016] present an example of a mesoscale eddy driving locally enhanced mixing, eddies are also responsible for transporting anomalous water properties away from their source region. In this issue, *Zhao and Timmermans* [2015] describe eddies, originating by baroclinic instability at a water-mass front in the Canadian Basin, that transport Eurasian Basin water into the Canadian Basin. In particular, they describe the process of eddy formation and formulate an analytical model to explain the observed vertical scales of the eddies. Their study provides observational constraints for model studies of eddy generation at the Beaufort Gyre boundaries, and bounds on model resolutions required to adequately resolve these processes.

The modeling study of *Luneva et al*. [2015] highlights the importance of tidal effects at the shelf break, with tidal mixing leading to enhanced shelf-basin exchange; this integrates well with a shelf-basin exchange theme of FAMOS, including an observational study of these processes in this issue by *Jackson et al*. [2015]. *Jackson et al*. [2015] analyze processes in the shelf region that enable shelf-basin exchange, and ventilation of the Arctic halocline. Wind-driven offshore transport of the surface ocean and sea ice maintains an area of open water in which intensive and sustained ice-growth can generate dense water. The surface transport is compensated by deep upwelling, and *Jackson et al*. show that these wind-driven processes are essential in the creation of the dense source water that ventilates the cold layers of the Canada Basin halocline. These processes are strongly tied to eddy generation and fluxes (e.g., bolus fluxes) that are the subject of ongoing FAMOS studies related to halocline ventilation and Beaufort Gyre energetics.

3.5. Biogeochemistry and Ecosystems

While several ecosystem and biogeochemistry (BGC) studies were completed during AOMIP-2 (see Table A4), the involvement of these communities has grown in FAMOS through truly coordinated, interdisciplinary model intercomparison studies. In this special issue, papers in this area analyze past and future changes in ocean productivity [*Yool et al*., 2015; *Jin et al*., 2016], phytoplankton response to ice free ocean conditions [*Lawrence et al*., 2015] and the future of the subsurface chlorophyll-a maximum [*Steiner et al*., 2016].

Yool et al. [2015] investigated changes in Arctic Ocean and North Atlantic productivity in the 21st century forced by climate warming. They employed two coupled ocean-ice-BGC models of different spatial resolutions to project future productivity changes, with a particular emphasis on the spring bloom. They found that productivity declines in the North Atlantic while increasing in the Arctic Ocean, and hypothesized that the Atlantic decrease is largely driven by reduced surface nutrient levels resulting from reduced deep mixing. On the other hand, the simulated increase in Arctic productivity is driven by increased light owing to reduction of sea ice. An encouraging conclusion is that lower resolution model results are commensurate with high-resolution simulations, suggesting that some first-order drivers may be well-captured without the need to resolve the small scales.

Lawrence et al. [2015] examined the impact of sea ice retreat on phytoplankton production in the Arctic Ocean, and showed good agreement with the conclusions of *Yool et al*. [2015]: patterns of phytoplankton production in the future reflect the distribution of nitrate and the availability of light. *Lawrence et al*. [2015] are careful to point out that our poor baseline understanding of the present phytoplankton distributions, and uncertainty in the mechanisms by which these distributions respond to external drivers, contribute to major uncertainty in future projections.

This caution is well supported by the results of *Lee et al*. [2015] (this issue) who assessed the skill and sensitivity of 32 net primary production (NPP) models for the Arctic Ocean based with inputs from in situ, reanalysis, and satellite data. Their goal of identifying primary areas of NPP model uncertainty is a key step in improving BGC/ecosystem modeling through FAMOS activities.

Steiner et al. [2016] analyzed results from six Earth system and three ocean-ice-ecosystem models to understand changes in the subsurface chlorophyll maximum (SCM). They found that simulated differences in SCM changes in the Canada Basin are due mainly to model inconsistencies in nutrient availability and differences in the represented ecosystem community structure among the models. The authors further noted that model differences in physical variables (e.g., sea ice conditions, and Beaufort Gyre dynamics) were significant and factored in the simulated SCM differences.

Last on the topic of primary productivity, *Jin et al*. [2016] (this issue) examined trends in under ice and total primary production associated with changes in sea ice extent over the satellite era. Their ecosystem model results of under ice primary production were highly sensitive to light availability, which is computed by atmospheric and sea ice models. This outcome motivates continued FAMOS model intercomparison studies that integrate biology with the atmosphere-sea-ice-ocean components.

4. Future Plans: FAMOS-2

Moving forward, the overall goal of FAMOS remains the same: to enhance understanding of processes and mechanisms driving Arctic oceanic and sea ice change. The major new focus of the second phase of FAMOS (FAMOS-2) is a consideration of models and observations at high (i.e., mesoscale) and very high (i.e., submesoscale and finer) spatial and temporal resolution to investigate the role of subgrid-scale processes in regional and pan-Arctic models.

Specific research themes for FAMOS-2, identified by participants of the Fourth FAMOS meeting in 2015, include: eddies, ocean freshwater and heat dynamics, sea ice processes, Atlantic water transformations, ecosystem and biogeochemical processes, and internal waves. The details of the coordinated studies, outlined briefly below, are posted at the FAMOS website.

4.1. Eddies

Motivated in part by studies in this issue which point to the key role of mesoscale eddies in Beaufort Gyre dynamics, as well as major intermodel differences depending on their eddy-resolving capabilities, a thrust of FAMOS-2 will be on model simulations resolving eddies. This theme will incorporate continued analyses of high-resolution observations to understand eddy impacts on freshwater and heat transport, and in regulating the large-scale flow.

4.2. Freshwater Dynamics

Studies related to Beaufort Gyre freshwater accumulation and release, river discharge, and Pacific Water inflow will continue to examine the role of small-scales processes. Recent studies have linked an accelerating Greenland melt with increasing freshwater fluxes to the surrounding seas over the last decade. It is hypothesized that these freshwater fluxes can reduce deep convection in the Labrador, Nordic, and Irminger seas. This hypothesis motivates the questions: What are the pathways of Greenland freshwater in the sub-Arctic seas, and what are the mechanisms of freshwater transport to the convection regions?. To address these questions in FAMOS-2, high-resolution numerical experiments will be performed, and analyzed in context with observations.

4.3. Sea Ice Processes

The goal of coordinated sea-ice investigations is to marry emerging results from the observational community with theoretical developments in sea ice physics. This will allow FAMOS-2 teams to establish a strategy for advancing high-resolution (order 10 km in the horizontal) sea ice simulation toward very high-resolution (order 1 km and finer) numerical modeling of sea ice. This work will focus on ways to achieve this so that the strategy accommodates fundamental spatiotemporal scales not just in sea ice itself, but also in coupling sea ice models to eddy-resolving ocean models and mesoscale atmospheric models. Through close interaction with FAMOS biogeochemistry high-resolution modeling teams, it is anticipated that this research will improve understanding of biogeochemical and ecosystem feedbacks with sea ice.

4.4. Atlantic Water Transformations

Investigation of Atlantic water (AW) transformation along its pathways will focus on high-resolution modeling. High and very high-resolution modeling and process studies are needed to correctly resolve multifaceted tidal interactions and mixing processes, wind-driven upwellings and downwellings, internal waves and eddies.

4.5. Biogeochemical and Ecosystem Modeling

Numerical modeling of biogeochemical and ecosystem process with high and very high-resolution may contribute understanding on the organization, functioning, and vulnerabilities of the Arctic marine ecosystems. Major breakthroughs will require both innovative modeling and observational techniques (e.g., in situ imaging of plankton and particles). These and many other technical, observational, and modeling limitations will be analyzed in the next phase of FAMOS.

4.6. Internal Waves

Mixing processes associated with internal waves (IW) impact ocean heat transport, sea-ice formation, and biological systems, propagation of acoustic signals and under-water navigation. However, the locations of enhanced IW activity and mixing in the Arctic Ocean remain unclear. The goal of this FAMOS activity is to identify the major hotspots and characteristics of internal solitary waves in the Arctic Ocean, using satellite altimetry and very high-resolution (up to 15 m in the horizontal) numerical modeling.

4.7. FAMOS for the Year of Polar Prediction

Each of the themes outlined above coordinates with the activities of the World Meteorological Organization's (WMO) project "Year of Polar Prediction" (YOPP), which will have a core phase in 2017–2019. One significant contribution of YOPP to FAMOS coordinated experiments will be accurate and high spatiotemporal resolution atmospheric forcing data.

Appendix A

Publications, sorted by general themes, are listed in the tables in this Appendix. Studies are grouped for AOMIP-1 1999–2007 (Tables A1–A3), AOMIP-2 2008–2012 (Table A4) and FAMOS-1 2013–2016 (Table A5).

Table A1. AOMIP-1 Model Intercomparison and Validation Studies in 1999–2007

Sea ice drift	*Wang et al.* [2005].
Sea ice concentration	*Kauker et al.* [2003]; *Hu et al.* [2004]; *Johnson et al.* [2007]
Sea ice thickness	*Martin and Gerdes* [2007]; *Gerdes and Köberle* [2007]
Sea level	*Proshutinsky et al.* [2001b, 2004, 2007]
Circulation	*Proshutinsky* [2003a, 2003b]; *Karcher et al.* [2003, 2007], *Karcher and Harms* [2004]; *Zhang* [2004]; *Drange et al.* [2005]; *Panteleev et al.* [2007]
Hydrography	*Steele et al.* [2001]; *Holloway et al.* [2007].

Table A2. AOMIP-1 Intercomparison Studies Suggesting Model Improvements in 1999–2007

Forcing biases	*Hunke and Holland* [2007]; *Makshtas et al.* [2007]
Vertical and lateral mixing	*Zhang and Steele* [2007]; *Karcher et al.* [2007]; *Golubeva and Platov* [2007]
Neptune effect	*Holloway et al.* [2007]
Advection schemes	*Maqueda and Holloway* [2006]; *Hofmann and Maqueda* [2006]
Restoring	*Steele et al.* [2001]; *Zhang and Steele* [2007];
Sea ice dynamics schemes	*Hibler et al.* [2006]; *Lipscomb et al.* [2007]

Table A3. AOMIP-1 Arctic Change and Process Studies in 1999–2007

Water circulation	*Gerdes et al.* [2003]; *Karcher and Oberhuber* [2002], *Karcher et al.* [2003, 2007]; *Golubeva and Platov* [2007]; *Zhang and Steele* [2007]; *Joyce and Proshutinsky* [2007]; *Proshutinsky* [2003a, 2003b]
Arctic sea level rise and causes	*Proshutinsky et al.* [2002b, 2004, 2007]
Freshwater dynamics	*Steele et al.* [2001]; *Proshutinsky et al.* [2002, 2005]; *Häkkinen and Proshutinsky* [2004]; *Steiner et al.* [2004]; *Uotila et al.* [2005]; *Köberle and Gerdes* [2007]; *Yang* [2006, 2009]
Ocean and sea ice changes	*Proshutinsky et al.* [2001a, 2005]; *Yakovlev* [2003]; *Kauker et al.* [2003]; *Maslowski et al.* [2004]; *Gerdes et al.* [2005]
Climate change	*Karcher et al.* [2003]; *Gerdes et al.*, [2003]; *Zhang et al.* [2004]; *Wang et al.* [2005]; *Karcher and Harms* [2004]; *Goosse et al.* [2004]; *Dukhovskoy et al.* [2004, 2006a, 2006b]; *Rinke et al.* [2006]
Arctic tides	*Hibler et al.* [2006]; *Holloway and Proshutinsky* [2007]

Table A4. AOMIP-2 Studies in 2008–2012

Bering Sea volume, heat, and salt fluxes	*Panteleev et al.* [2010]; *Proshutinsky et al.* [2011]; *Clement-Kinney and Maslowski* [2012]
Canada Basin shelf-basin exchange and mechanisms	*Watanabe*, [2011]; *Proshutinsky et al.* [2011]
Pacific and Atlantic water circulation studies	*Aksenov et al.* [2010, 2011]; *Karcher et al.* [2003, 2008, 2012]; *Proshutinsky et al.* [2011]
Halocline studies	*Watanabe* [2011]; *Platov et al.* [2011a, 2011b]
Freshwater pathways, accumulation, and release	*Aksenov et al.* [2010]; *Döscher et al.* [2010]; *Golubeva* [2010]; *Houssais and Herbaut* [2011]; *McGeehan and Maslowski* [2012]; *Proshutinsky et al.* [2011]; *Gao et al.* [2011]; *Kuzin et al.* [2010]; *Long et al.* [2012]; *Proshutinsky et al.* [2012]; *Rabe et al.* [2013]; *Timmermans et al.* [2011];
Reanalysis of hydrography and circulation, sensitivity studies	*Panteleev et al.* [2010]; *Fenty* [2010]; *Heimbach* [2008]; *Kauker et al.* [2009]; *Golubeva and Platov* [2009], *Golubeva* [2010]; *Heimbach et al.* [2011];
Design of an Arctic Ocean observing system based on Observing System Simulation Experiments	*Calder et al.* [2010]; *Heimbach et al.* [2010a]; *Lique and Steele* [2013]
Sea ice modeling and validation	*Heimbach et al.* [2010b]; *Johnson et al.*, [2012]; *Rampal et al.* [2011]; *Lemieux et al.* [2008, 2010]; *Lemieux and Tremblay* [2009]

Table A5. FAMOS-1 Studies in 2013–2016

Ecosystem studies	*Greene et al.* [2013]; *Popova et al.* [2013, 2014]; *Yool et al.* [2015]; *Lawrence et al.* [2015]; *Jin et al.* [2016]; *Steiner et al.* [2016]; *Lee et al.* [2015]
Tides	*Luneva et al.* [2015]
Major circulation	*Aksenov et al.* [2016], *Dukhovskoy et al.* [2016]
Ocean temperature, heat, freshwater	*Proshutinsky et al.* [2013]; *Rabe et al.* [2014]; *Pemberton et al.* [2014]; *Lique et al.* [2014]; *Stroh et al.* [2015]; *Granskog et al.* [2015]; *Ding et al.* [2016]; *Timmermans and Proshutinsky* [2015]
Ocean dynamics	*Yang et al.* [2016]; *Pemberton and Nilsson* [2015]; *Nummelin et al.* [2016]
Eddies	*Zhao et al.* [2014]; *Zhao and Timmermans* [2015]; *Manucharyan and Spall* [2016]; *Bebieva and Timmermans* [2016]
Regional ocean process studies	*Smedsrud et al.* [2011, 2013]; *Long and Perrie* [2013]; *Zhong and Zhao* [2014]; *Timmermans et al.* [2014]; *Jackson et al.* [2014, 2015]; *Janout et al.* [2015]; *Marnela et al.* [2016]; *Panteleev et al.* [2016]
Ice: Melt ponds	*Webster et al.* [2016]; *Roy et al.* [2015]; *Abraham et al.* [2015];
Ice: physics	*Tsamados et al.* [2013]; *Lemieux et al.* [2015]; *Martin et al.* [2014, 2016]; *Rabatel et al.* [2015]; *Hata and Tremblay* [2015a, 2015b]
Ice: state, statistics, and predictions, fast ice, ice drift	*Krishfield et al.* [2014]; *Onarheim et al.* [2014]; *Steele and Ermold* [2015]; *Schweiger and Zhang* [2015]; *Hebert et al.* [2015]; *Close et al.* [2015]; *Dukhovskoy et al.* [2015]; *Selyuzhenok et al.* [2015]; *Olason* [2016], *Petty et al.* [2016]
Climate	*Proshutinsky et al.* [2015]; *Long and Perrie* [2015]

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