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Modeling the Arctic freshwater system and its integration in the global system: Lessons learned and future challenges

Camille Lique[1,2], Marika M. Holland[3], Yonas B. Dibike[4], David M. Lawrence[5], and James A. Screen[6]

[1]Department of Earth Sciences, University of Oxford, Oxford, UK, [2]Ifremer, Laboratoire de Physique des Océans, UMR6523, CNRS-IFREMER-IRD-UBO, Brest, France, [3]Climate and Global Dynamics Division, National Center for Atmospheric Research, Boulder, Colorado, USA, [4]Environment Canada, Water and Climate Impacts Research Centre at the University of Victoria, Victoria, Canada, [5]National Center for Atmospheric Research, Boulder, Colorado, USA, [6]College of Engineering, Mathematics and Physical Sciences, University of Exeter, Exeter, Devon, UK

Key Points:
- The use of a model hierarchy is a powerful tool to study the Arctic freshwater system functioning
- Model improvements are needed to narrow projection uncertainty associated with model deficiencies
- New strategies and validation tools will be useful in improving models moving forward

Correspondence to:
C. Lique,
camille.lique@ifremer.fr

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Abstract Numerous components of the Arctic freshwater system (atmosphere, ocean, cryosphere, and terrestrial hydrology) have experienced large changes over the past few decades, and these changes are projected to amplify further in the future. Observations are particularly sparse, in both time and space, in the polar regions. Hence, modeling systems have been widely used and are a powerful tool to gain understanding on the functioning of the Arctic freshwater system and its integration within the global Earth system and climate. Here we present a review of modeling studies addressing some aspect of the Arctic freshwater system. Through illustrative examples, we point out the value of using a hierarchy of models with increasing complexity and component interactions, in order to dismantle the important processes at play for the variability and changes of the different components of the Arctic freshwater system and the interplay between them. We discuss past and projected changes for the Arctic freshwater system and explore the sources of uncertainty associated with these model results. We further elaborate on some missing processes that should be included in future generations of Earth system models and highlight the importance of better quantification and understanding of natural variability, among other factors, for improved predictions of Arctic freshwater system change.

1. Introduction

The Arctic climate is undergoing unprecedented and drastic changes, affecting all the components of the Arctic system [e.g., *Serreze et al.*, 2006; *Rowland et al.*, 2010; *Bhatt et al.*, 2014; *Wu et al.*, 2005]. Many of these changes affect the hydrological cycle and the freshwater budget of the Arctic region [e.g., *White et al.*, 2007, *Prowse et al.*, 2015a]. Changes of the Arctic freshwater system have gained considerable interest, since they have the potential to strongly influence the terrestrial carbon cycle [*Wrona et al.*, 2016], the global ocean circulation [*Jahn and Holland*, 2013], and future sea level rise [*Rignot et al.*, 2011]. The transformations currently underway are expected to intensify in the future in response to rising greenhouse gas emissions in the atmosphere [*Intergovernmental Panel on Climate Change (IPCC)*, 2013].

Over the last decade, there has been an increasing effort within the scientific community to better observe the different components of the Arctic freshwater system. For instance, oceanic gateways to the Arctic have been monitored, so that the freshwater flux to the Arctic can be reasonably quantified [*Beszczynska-Moller et al.*, 2011; *Tsubouchi et al.*, 2012]. Satellite observations and satellite-derived products provide us with a description of the sea ice pack, including concentration [e.g., *Comiso et al.*, 1997], thickness [*Laxon et al.*, 2003; *Kwok et al.*, 2009], ice age, and ice motion [e.g., *Emery et al.*, 1995]. The number of stations to measure precipitation has increased [*Cullather and Bosilovich*, 2012], improving the quality of the atmospheric reanalysis products in which the observations are assimilated [*Lindsay et al.*, 2014] although considerable deficiencies still exist (see discussion in *Vihma et al.* [2016]). Efforts to monitor the pan-Arctic river discharges to the Arctic oceanic basin are ongoing through international programs such as the United Nations Global Environment Monitoring System Water Program or the US-funded Arctic Great Rivers Observatory project (http://www.arcticgreatrivers.org). Yet the current monitoring system does not comprehensively cover all areas draining to the ocean, and the number of stations has decreased [*Bring and Destouni*, 2009, 2014; *Bring et al.*, 2016].

Despite these recent advances in observations, it still remains challenging to estimate a closed freshwater budget for the Arctic region from observations, and the observational time series span too short a period to reliably estimate the interannual-to-decadal variability of the different terms of the freshwater budget. As a result, modeling tools have been widely used to investigate the Arctic freshwater system. Indeed, the first purpose of using models has often been to fill some of the gaps in observations. This is most notably the case for reanalysis products in which observations are assimilated [e.g., *Dee et al.*, 2011; *Kalnay et al.*, 1996]. The lack of observations often does not allow for a proper evaluation of the model realism or constraint of the model solutions for reanalysis efforts. As such, model results need to be considered in light of this uncertainty regarding model performance. Models have also been widely used to inform the understanding of mechanisms of variability and change affecting the different components of the Arctic freshwater system, and to attribute some changes to human influence.

The goal of the current paper is to review the progress made in our understanding of the Arctic freshwater system using modeling tools. This does not include a comprehensive review of all the modeling studies in which one component or the full Arctic freshwater budget has been investigated but rather provides relevant examples to illustrate how different types of models can be used to study the Arctic freshwater system. This paper is a contribution to the “Arctic Freshwater Synthesis” (http://www.climate-cryosphere.org/activities/targeted/afs), which is a joint effort to review our current knowledge on the functioning of the Arctic freshwater system. Hence, the reader should refer to the other papers in this special issue for more details regarding the historical and predicted future changes affecting the different components of the freshwater system [see *Prowse et al.*, 2015a, 2015b; *Carmack et al.*, 2015; *Bring et al.*, 2016; *Vihma et al.*, 2016; *Instanes et al.*, 2016; *Wrona et al.*, 2016].

The remainder of this paper is organized as follows. In section 2, we address the question of how models from different categories have been used to investigate different aspects of the Arctic freshwater system. In section 3, we present a review of modeling studies investigating historical and projected changes of the Arctic freshwater system, and the mechanisms and drivers of these changes. Section 4 is dedicated to the integration of the Arctic freshwater system within the global climate system. We then discuss the gaps of our current knowledge and the need of future model developments to better understand the Arctic freshwater system (section 5), followed by conclusions in section 6.

2. Using Models as a Tool to Understand the Arctic Freshwater System

2.1. The Importance of a Hierarchy of Modeling Approaches

Scientific models used to understand the Earth system (Figure 1) take many forms, from conceptual models that illustrate the logic behind a particular hypothesis, to complex numerical models that solve systems of equations that together depict system functioning. Models are an integral and necessary part of the scientific process and provide a powerful tool for developing and testing hypotheses. They allow for controlled experiments to diagnose mechanisms and interactions that influence system functioning and provide predictive capability, allowing us to assess the system response to forcing perturbations. While powerful tools, models are always simplifications of the real system, a fact that must be considered when evaluating and generalizing their results.

The use of a hierarchy of models is necessary to gain improved understanding of the Arctic freshwater system (or climate system more generally), its interworkings, and the implications of those workings [e.g. *Held*, 2005]. This hierarchy can be defined in many different ways but essentially includes models of different levels of complexity and component interactions. Studies of the Arctic freshwater system, or elements thereof, have benefitted from the use of many different types of models to gain understanding. For example, *conceptual models* [e.g. *Francis et al.*, 2009] have been designed to illustrate how previously diagnosed linkages across the Arctic hydrologic system give rise to potential feedbacks. While a model of this sort is unable to quantify feedback strength, it does provide insight on where important interactions occur and can identify key gaps and uncertainties in our current knowledge. This knowledge can then inform experimentation with other

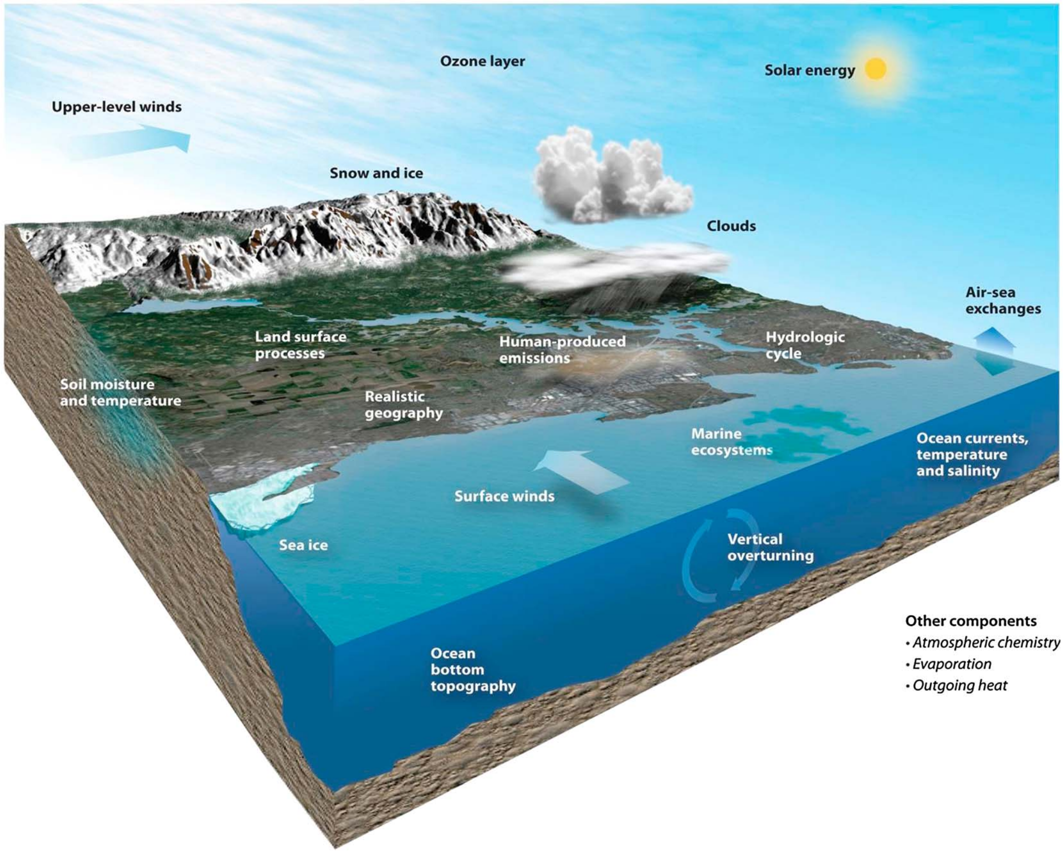

Figure 1. A schematic illustrating processes represented in an Earth system model. *Process models* may focus on single elements of this schematic (such as clouds or sea ice thermodynamics), *component models* isolate a particular component of the system subject to specified boundary conditions (such as ocean-only models or atmosphere-only models), and *fully coupled Earth system models* include interactions across multiple components and may also incorporate interactions and simulations with biogeochemical cycles, among others. Copyright UCAR. Illustration courtesy of Warren Washington, NCAR.

types of models, motivate field measurements to better quantify climate interactions or highlight testable hypotheses in need of further research.

Process models, which we define as models that are isolated to the simulation of a specific element of the system, also play a critical role in advancing our understanding on key aspects of the Arctic freshwater system. This includes work to better understand sea ice processes [e.g., *Feltham et al.*, 2006; *Notz and Worster*, 2009; *Turner et al.*, 2013], permafrost dynamics [e.g., *Lawrence et al.*, 2008; *Frampton et al.*, 2013], high-latitude lakes [*Dibike et al.*, 2011], snow cover evolution [e.g., *Liston and Elder*, 2006], ocean shelf plume mixing [e.g., *Anderson et al.*, 1999], Arctic cloud processes [e.g., *Morrison and Gettelman*, 2008], and terrestrial Arctic ecosystem dynamics [e.g., *Euskirchen et al.*, 2006; *McGuire et al.*, 2012], among others. Process modeling enables an enhanced understanding of factors that determine the evolution of an isolated piece of the system, which is useful in its own right. Additionally, depending on their level of detail, these process models can be incorporated directly into large-scale component models or can inform parameterization development for large-scale models. As one example, *Polashenski et al.* [2012] developed a process model of meltwater percolation through sea ice that provided new insight on mechanisms of sea ice melt pond formation and evolution. This has ultimately informed more physically based parameterizations of ponds within large-scale models [e.g., *Flocco et al.*, 2012; *Hunke et al.*, 2013].

Component models, which are large-scale models isolated to a single Earth system component (e.g., atmosphere, ocean, land, sea ice, or ice sheet), have been used to investigate mechanisms of variability and change in the Arctic freshwater system. These models can be global or regional (e.g., Arctic only) in scope, can have different levels of complexity, and can have vastly different resolutions. In many component studies, including the ones primarily discussed here, the models used are equivalent to uncoupled components of global coupled climate models. These models are driven by specified boundary information, often from the historical record. For example, the Arctic Ocean Model Intercomparison Project (AOMIP) [*Proshutinsky et al*., 2001] utilized simulations from ocean-sea ice coupled models that were forced by prescribed atmospheric reanalysis conditions over the historical record. Similarly, land models can be run off-line, forced with historic surface reanalysis data, to study how the terrestrial ecohydrological system responds to climate and climate change [*Lettenmaier and Su*, 2012]. The use of observationally based forcing has the advantage that the time evolution of simulated conditions will have a similar trajectory to the observed state, thereby permitting more direct comparisons to observational data. However, the outcomes of these simulations can be strongly dependent on the specified observed forcing, which for some fields such as precipitation are highly uncertain in high latitudes [*Su et al*., 2005]. The resolution of the forcing data sets used to drive component model simulations is also potentially problematic. For example, *Whitefield et al*. [2015] showed that Arctic shelf freshwater content in high-resolution ocean-ice simulations was strongly dependent on the resolution of the river discharge forcing data set.

Component models have also been used for regional downscaling, often driven by boundary forcing from global climate model projections [e.g., *Dibike et al*., 2008]. Although the results from the regional downscaling are highly sensitive to both the method used for the downscaling [e.g., *Fowler et al*., 2007] and the model used [e.g., *Benestad et al*., 2002], these methods can provide much higher resolution and more detailed information for isolated regions, which can be useful for determining resource needs and risks (for more discussion, see *Instanes et al*. [2016]). Component models of this type do not include interactions and feedbacks between other system components (e.g., air-sea or surface turbulent heat fluxes will not affect the prescribed atmospheric boundary conditions in an ocean- or land component-only model simulation). This can modify simulated variability characteristics [e.g., *Blanchard-Wrigglesworth and Bitz*, 2015, for sea ice thickness variability] and affect the relative importance of different flux terms. As such, given that these interactions can strongly modify system behavior, results need to be carefully considered.

Coupled climate models explicitly consider coupled interactions and generally include atmosphere, ocean, sea ice, and terrestrial components. More recently, these coupled systems have evolved into Earth system models (ESMs), which can also incorporate biogeochemical cycles, atmospheric chemistry, and land ice components [e.g., *Collins et al*., 2011; *Dunne et al*., 2012; *Giorgetta et al*., 2013; *Hurrell et al*., 2013]. This allows for additional coupled interactions, and the simulation of carbon cycle and ice sheet dynamics. Coupled models can be regional or global in scope. Regional models [e.g., *Maslowski et al*., 2012; *Roberts et al*., 2015] require specified lateral boundary information and have no feedbacks to the global system. However, regional models can generally be run at considerably higher resolution because of the reduced spatial domain. For global models, the Coupled Model Intercomparison Project (CMIP) has coordinated sets of coupled experiments for historical and projected future conditions for different scenarios (or representative concentration pathways (RCPs)). Analysis of the results from the third [*Meehl et al*., 2005] and fifth [*Taylor et al*., 2012] phases of CMIP (referred to as CMIP3 and CMIP5) has allowed for a more consistent comparison across different models. Coupled models allow us to examine mechanisms that give rise to coupled feedbacks and through the design of individual experiments can be used for hypothesis testing. They also are used to detect and attribute long-term observed change to different external forcings. For example, *Min et al*. [2008] used coupled model information to assess a detectable influence of anthropogenic forcing on Arctic sea ice since the early 1990s.

While coupled models are powerful tools, the downside to their use is that simulations can exhibit considerable biases when compared to observations. As one example, the mean Arctic sea ice thickness over the period 2003–2008 ranges from 0.5 m to 3 m in CMIP3 models, compared to the 2 m estimated by Ice Cloud and Land Elevation Satellite (ICEsat) over the same period [*Rampal et al*., 2011]. These biases also tend to propagate to the estimates obtained from downscaling methods based on climate model outputs. This is for instance visible in the study of *Koenigk et al*. [2015], in which results from different CMIP5 models are downscaled over the Arctic region, using a regional Arctic atmospheric model. They found that the results from the downscaling mostly reflect the biases found in the representation of the Arctic present-day conditions by the different global climate models.

Advancing our understanding of the Arctic freshwater system requires the use of models across the hierarchy discussed above. This can often take an iterative approach. For example, conceptual and process models can identify important factors that may influence system functioning. Component and coupled models can then be used to further investigate these factors subject to additional climate system interactions. Below, we illustrate how models have been used to understand historical and projected changes within the Arctic freshwater system. This primarily relies on results from component and coupled model systems. However, these models and their simulation fidelity have clearly benefitted from knowledge gained in process and simpler modeling studies. Avenues to promote the integration of scientists working across this hierarchy, and to more efficiently share the knowledge gained across the different modeling types and with the observational community, are needed for continued enhancements in our understanding of Arctic freshwater change and its implications.

2.2. Model Limitations

All models are by necessity simplifications of a complex system and can omit processes of relevance to a specific problem. In the case of the Arctic freshwater system, large-scale climate models have generally excluded ice sheet models and glacier systems. As such, they cannot simulate changes in land ice characteristics, although they do often include changes in the snow cover on top of ice sheets. Some ESMs have incorporated Greenland ice sheet (GIS) models [e.g., *Yoshimori et al*., 2001; *Ridley et al*., 2005; *Vizcaíno et al*., 2013; *Lipscomb et al*., 2013], but this is quite recent and not very widespread. Additionally, large-scale models typically exclude lake processes or treat them simplistically as a one-dimensional column of water and exclude many aspects of river networks, such as their capacity to freeze and transport heat, carbon, nutrients, and sediment. This has implications for the simulation of feedbacks and cross-component interactions associated with these processes. For example, changes in the timing of river discharge can influence the seasonality of riverine nutrient transport with potential impacts on marine ecosystems phenology, or the heat flux associated with the riverine input to the ocean can reduce significantly the sea ice extent (by up to 10% [*Whitefield et al*., 2015]). This is not included in current-generation ESMs.

Model biases need to be understood and considered in all model analyses of the Arctic freshwater system. One well-known weakness of the latest atmospheric models, such as those used in the CMIP3/CMIP5, is their inability to accurately simulate Arctic cloud cover. The Arctic maritime environment is dominated by low-level cloud, with 60–80% annual mean low-level cloud cover according to the estimate from satellite lidar [*Cesana and Chepfer*, 2012]. The CMIP5 models generally underestimate this low-level cloud cover, but with large intermodel spread (40–70% [*Cesana and Chepfer*, 2012]). Furthermore, whereas observations show two annual maximum in low-level cloud cover, in spring and autumn, models generally depict a single summer maximum [*Cesana and Chepfer*, 2012]. The seasonal cycle of total cloud cover is better simulated, but again with large spread [*Karlsson and Svensson*, 2013]. Documented model biases in the near-surface temperature inversion, which is typically too strong [*Medeiros et al*., 2011], may be related to these cloud deficiencies. Such biases in the mean state may be partly responsible for the large model spread in future projections [e.g., *Vihma et al*., 2016]. More details on atmospheric model biases are discussed in *Vihma et al.* [2016].

Large-scale atmospheric model components of ESMs are run at a quite coarse resolution (~100 km) and do not resolve some processes of importance to Arctic hydrology. For example, topographic controls on precipitation are often not well simulated, leading to biases in the regional characterization of rain and snowfall [e.g., *Finnis et al*., 2009]. There is evidence that models with a higher horizontal resolution have a more realistic depiction of cyclone track and polar lows [*Zappa et al*., 2013]. Some studies suggest that current-generation atmospheric models have insufficient vertical resolution. Improved vertical resolution may be necessary to better simulate boundary layer processes [*Byrkjedal et al*., 2008] and stratospheric variability [*Charlton-Perez et al*., 2013] and, therefore, the simulated Arctic atmosphere. Note that atmospheric models, combined with observations, are also used to produce atmospheric reanalyses, which are further used as atmospheric forcing for ocean or terrestrial models [e.g., *Lindsay et al*., 2014]. When using these forcing fields, one cannot expect to reproduce the effects of some of the processes operating at smaller scales than the resolution of the atmospheric models, even in case when the ocean or terrestrial model is run at a higher resolution.

In the terrestrial realm, cold region hydrological processes such as sublimation and redistribution of blowing snow [*Bowling et al*., 2004], the role of surface water storage in lakes and wetlands on the seasonal river hydrographs [*Bowling et al*., 2000, 2003], the unique hydrological impact of organic soils [*Lawrence and*

Slater, 2008], infiltration limitation by frozen soils [*Swenson et al*., 2012], and even some general snow processes such as snow insulation [*Koven et al*., 2013] are still not well represented in some land surface models (LSMs). Permafrost dynamics, which exerts strong controls on Arctic hydrology as discussed by *Bring et al.* [2016], has only recently received explicit attention in large-scale LSMs, leading to significant improvements [*Riseborough et al*., 2008; *Lawrence et al*., 2008, 2012; *Dankers et al*., 2011; *Ekici et al*., 2013]. Most LSMs now include freeze-thaw processes and are advancing with more targeted development efforts to improve cold region soil hydrology by incorporating concepts such as a perched or suprapermafrost water table [*Swenson et al*., 2012]. However, *Koven et al*. [2013] and *Slater and Lawrence* [2013] assessed CMIP5 output and found that the majority of current-generation ESMs do not reasonably simulate present-day permafrost conditions. The poor simulation of permafrost can be attributed to several factors, including climate biases in the Arctic in many of the models as well as structural deficiencies in the LSMs including parameterization of land snow processes, too shallow soil columns [*Alexeev et al*., 2007; *Nicolsky et al*., 2007], poor coupling between soil temperature and hydrology, or the lack of some important dynamic processes such as those involved in thermokarst development, including thaw, ponding, surface and subsurface drainage, surface subsidence, and related erosion. Finer-scale features such as permafrost-controlled variations in hydrologic connectivity and the influence of subgrid-scale permafrost distribution on surface and groundwater systems are also not represented [*Woo et al*., 2008]. Massive ground ice, also referred to as excess ice, is another feature of permafrost systems that is not typically represented and which may both delay and alter the hydrologic response to permafrost thaw [*Lee et al*., 2014]. While there has been substantial progress from an observational and experimental perspective in understanding cold region hydrological processes, challenges remain to incorporate the latest process understanding in ESMs. There is also increasing emphasis, through projects such as Next-Generation Ecosystem Experiments Arctic (http://ngee-arctic.ornl.gov/), to employ a nested hierarchy of models at fine, intermediate, and climate scales through which increased process understanding can be incorporated into models of appropriate scale and through which upscaling and downscaling can be evaluated [e.g., *Painter et al*., 2013; *Riley and Shen*, 2014].

Focusing on hydrology, the deficiencies discussed above have related effects on the simulation of seasonal variations in freshwater discharge to the Arctic. Using the Variable Infiltration Capacity (VIC) LSM, *Su et al*. [2005] found that model performance is highly sensitive to the precipitation forcing, which as noted previously is highly uncertain due to sparse measurements in the Arctic. Results from multimodel simulations of pan-Arctic hydrology by *Slater et al*. [2007] found up to a 30% difference across models in the annual partitioning of precipitation into evaporation and runoff over major Arctic watersheds. The models, on average, did not accurately represent base flow of the major rivers, and the model hydrographs tended to peak too early relative to observed river flow [*Slater et al*., 2007]. Finally, due to limitations in LSMs (i.e., poorly represented permafrost dynamics and permafrost hydrology), virtually all large-scale modeling studies of the Arctic runoff response to historic and future climate change have not realistically incorporated any potential impact of permafrost thaw and soil ice melt on soil water drainage and runoff. Consequently, the hypothesis put forth by *St Jacques and Sauchyn* [2009] that historic observed increases in winter base flow can be attributed to enhanced infiltration and deeper flow paths resulting from permafrost thaw can neither be corroborated nor discredited by existing models. Efforts to assess this hypothesis with next-generation models should be a priority.

Spatial scaling issues are problematic across different component systems and present challenges for translating observationally based process information that is site specific to a generalized model representation that works across climate regimes. Because of computational limitations, a relatively coarse resolution (of ~1° or so) is required for climate-scale integrations with fully coupled models. While these scaling issues are true globally, unique aspects of the Arctic system, including the permafrost hydrology interactions mentioned above and the presence of sea ice, provide additional challenges for this region. High spatial heterogeneity within the sea ice system or its overlying snowpack is not explicitly resolved in climate-scale models. This strongly influences simulated sea ice mass budgets [e.g., *Maykut*, 1982]. Some models do now incorporate subgrid-scale ice thickness distribution to better simulate these factors, which has been shown to influence not only the mean climate state but also the response to forcing perturbations and simulated feedbacks [e.g., *Holland et al*., 2006]. Sea ice models also have numerous missing processes, many of which are subgrid scale. For example, most large-scale models disregard many factors that influence the snow on sea ice, including the metamorphism of snow and its redistribution due to winds. These influence the sea ice thermal and radiative properties, and biases in snow on sea ice also impact the surface albedo evolution with consequences for climate feedbacks [e.g., *Holland and Landrum*, 2015]. Notably, sea ice model developments are addressing some of these processes, including improved sea ice hydrology and prognostic salinity [e.g., *Hunke et al*., 2011; *Turner and Hunke*, 2015], improved sea ice rheology [e.g., *Tsamados et al*., 2013], improved snow processes [*Lecomte et al*., 2013], and improved melt pond schemes [e.g., *Flocco et al*., 2012; *Hunke et al*., 2013]. These developments impact large-scale climate simulations, including the freshwater system, since they affect sea ice mass budgets and ice-ocean freshwater exchange.

For the ocean component, the necessary coarse resolution for climate integrations means that the climate models do not resolve any eddy activity in the Arctic region [*Nurser and Bacon*, 2014]. Additionally, complex channels, such as those through the Canadian Arctic Archipelago (CAA), are not well resolved (or nor resolved at all). Similarly, modeling the flow through Bering Strait is challenging because the strait is narrow (~85 km) and the observed water mass structure through the strait is complex [e.g., *Woodgate et al*., 2012] and thus requires a fine resolution to be properly represented. A proper representation of the flow through these different narrow pathways is crucial as it has implications for freshwater transport pathways [e.g., *Goosse et al*., 1997; *Gerdes et al*., 2008] as well as the Arctic circulation and the downstream controls on the Atlantic Meridional Overturning Circulation (AMOC) [*Wadley and Bigg*, 2002; *Lietaer et al*., 2008]. Within the ocean component models, processes of potential climate importance such as tides [e.g., *Holloway and Proshutinsky*, 2007], shelf plume dynamics [e.g., *Anderson et al*., 1999], near-coastal narrow boundary currents [*Carmack et al*., 2015], and the dense overflows through narrow or unresolved channels [e.g., *Danabasoglu et al*., 2010] are not generally represented in large-scale models. This can influence simulated water mass properties and variability, and many climate models have significant biases in their simulated temperature and salinity structure (Figure 2) [*Holland et al*., 2007]. As discussed by *Holloway et al*. [2007], ocean models also simulate considerably different Arctic circulations, even when driven by prescribed atmospheric conditions.

While models have limitations and existing biases, they remain a powerful tool to investigate the climate system functioning, including the functioning of the Arctic freshwater system. Models encapsulate our current system understanding and so can provide insight on where knowledge is insufficient, motivating future research needs. Models also provide a tractable means to test hypotheses. Observations and theory can suggest explanations for the occurrence of a specific phenomenon. However, testing these hypotheses within the climate system domain is challenging. Models provide us with a virtual laboratory where, through appropriate experimental design, controlled experiments are possible.

3. Using Models to Understand Historical and Projected Change in Arctic Freshwater Budgets

In this section, we review modeling studies investigating historical or future changes of one or several terms of the Arctic freshwater budget. The reader should refer to *Prowse et al.* [2015a] and *Carmack et al.* [2015] for more details on the various definitions of the Arctic domain. As we do not aim to present a closed budget for the Arctic, we adopt a loose definition of the Arctic domain, which might differ between the terrestrial and marine components of the Arctic system.

3.1. Past Changes and Key Drivers

The Arctic Ocean freshwater budget (Figure 3) consists of a net source of water from river runoff, the inflow of relatively fresh water from the Pacific through Bering Strait, and precipitation minus evaporation. This is largely balanced by a net export of water to the North Atlantic through ocean and sea ice transport via the CAA and Fram Strait. Relatively saline waters enter the Arctic through the Barents Sea Opening, representing a sink of freshwater for the Arctic. Freshwater is stored within the Arctic Ocean in the form of relatively fresh ocean waters in the surface layer and sea ice, which has a low salinity of about 4. Studies have generally assessed ocean freshwater storage and transports relative to a specified reference salinity, which is often 34.8 as it is thought to be the average salinity of the Arctic Ocean [*Aagaard and Carmack*, 1989], although different studies use different values. More information on issues involved in using a specific reference salinity is available in *Carmack et al.* [2015].

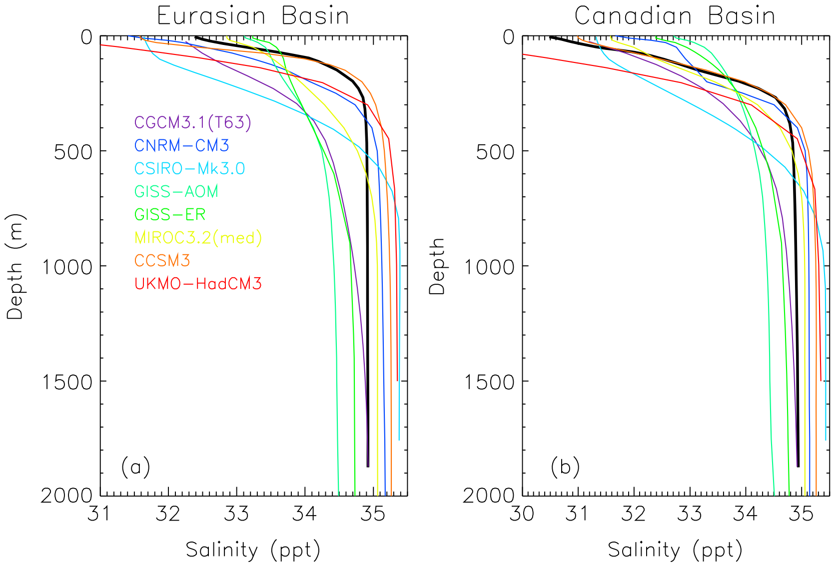

Figure 2. The 1990–1999 mean salinity profiles for different CMIP3 models averaged over (a) the deep Eurasian and (b) deep Canadian basins. The thick black line shows the Polar Science Center Hydrographic Climatology (PHC) observations [*Steele et al.*, 2001b]. The figure illustrates the deficiency of the state-of-the-art climate models in the representation of the ocean salinity, leading in important biases for the simulated Arctic freshwater content. Figure reprinted from *Holland et al.* [2007].

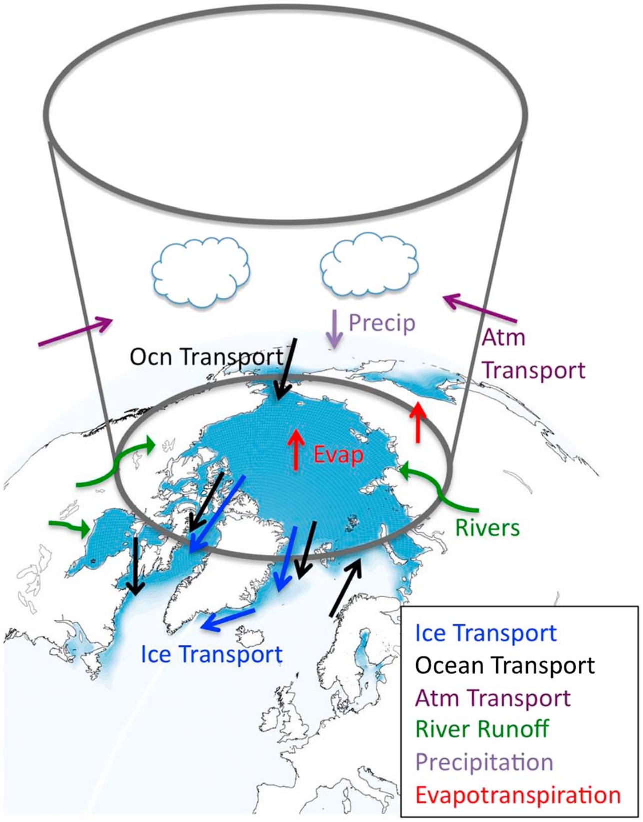

Figure 3. A schematic of the Arctic freshwater budget. The different arrows indicate the different terms contributing to the budget. Additionally, freshwater is stored within the Arctic region, in the forms of low-salinity water and sea ice in the ocean and snow, glaciers, groundwater, and permafrost ice over land. The blue background indicates the average March sea ice concentration for 1980–1989 from the Special Sensor Microwave Imager data.

Data scarcity, in both time and space, is a common problem for the Arctic sciences, and the study of the freshwater system is no exception. Variability and historical changes affecting the Arctic freshwater budget have thus been examined in numerous modeling studies, using different types of models ranging from single-component models to coupled climate models. Mechanisms driving the variability of some terms of the budget have also been examined using process models or idealized experiments [e.g., *Proshutinsky and Johnson*, 1997; *Stewart and Haine*, 2013; *Davis et al.*, 2014].

One valuable application of models has been in the production of atmospheric reanalysis data sets, which combine available observations with model-derived, but observationally constrained, estimates of unobserved quantities. Atmospheric reanalyses have been used to examine the time-mean Arctic freshwater budget [*Serreze et al.*, 2006] and variability and change in, for example, Arctic humidity [*Serreze et al.*, 2012] and precipitation [*Screen and Simmonds*, 2012]. They have also been harnessed to gain insight into driving mechanisms, for example, the contribution of atmospheric moisture transport

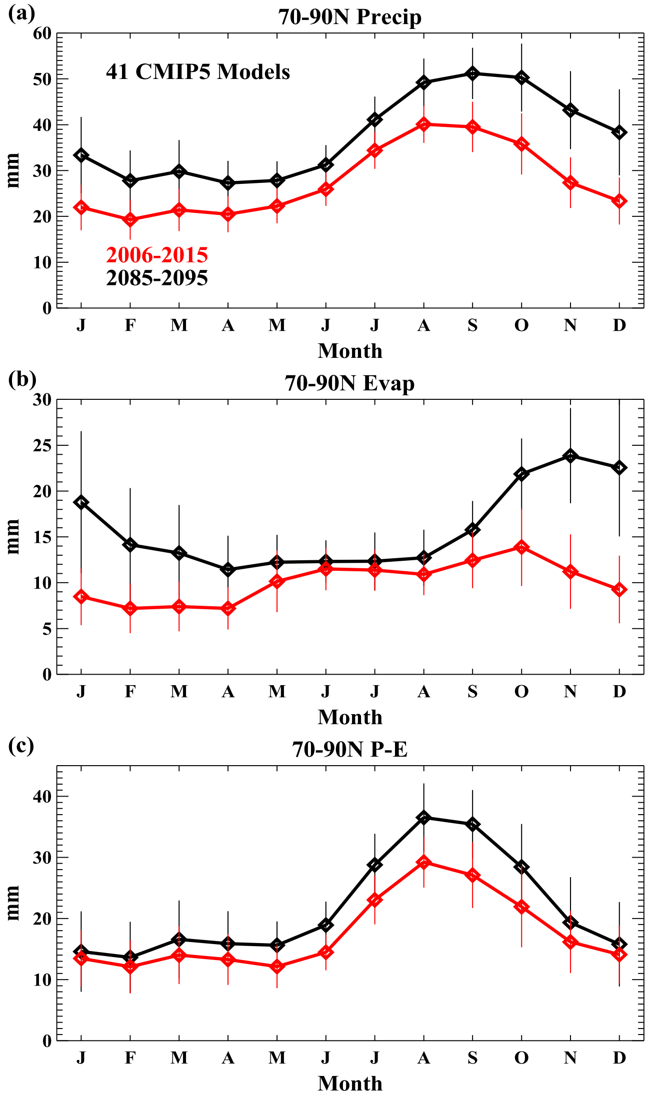

Figure 4. Multimodel averaged atmospheric freshwater flux terms for 70–90°N from CMIP5 models using the RCP8.5 forcing scenario. Shown are the annual cycle of (a) precipitation, (b) evaporation, and (c) net precipitation (P − E). The red line represents values from the early 21st century (2006–2015 average) and the black line from the late 21st century (2085–2095). Forty-one models are used in the analysis, and the vertical bars represent the standard deviation across the different models.

to Arctic precipitation trends [*Zhang et al.*, 2013] or the contribution of Arctic warming to summer snowfall declines [*Screen and Simmonds*, 2012]. Lastly, atmospheric reanalyses are often used to validate climate model output [e.g., *Skific et al.*, 2009; *Bengtsson et al.*, 2011]. One should keep in mind, however, that atmospheric reanalyses, although strongly constrained by observations, are based on models, and thus should be considered in light of their associated uncertainties. A recent intercomparison of seven different reanalyses in the Arctic region [*Lindsay et al.*, 2014] shows large differences among the different products for the mean, variability, and trend of most atmospheric fields, although no one reanalysis product stands out as more generally trustworthy than another. More information on deficiencies of the Arctic representation in atmospheric reanalyses is available in *Vihma et al.* [2016].

Kattsov et al. [2007] and *Holland et al.* [2007] have compared the atmospheric terms of the Arctic freshwater budget as simulated by the CMIP3 models. To our knowledge, no comprehensive assessment of the freshwater budget simulated by the CMIP5 models has been performed so far, although some groups have evaluated the performance of individual models to simulate the Arctic atmospheric conditions (e.g., CCSM4 [*de Boer et al.*, 2011]). Overall, CMIP3 models reproduce reasonably well the climatological spatial distribution of precipitation, although *Kattsov et al.* [2007] report a general overestimate of precipitation throughout much of the Arctic by CMIP3 models when compared with observed precipitation data sets. They attribute this mismatch between the simulated and observed precipitation to insufficiently resolve orography and biases in the large-scale atmospheric circulation and sea ice distribution. CMIP3 and CMIP5 models also reproduce qualitatively well the observed seasonal cycle in precipitation (Figure 4) as well as the observed positive trend in precipitation over the 20th century, with a larger trend in winter than summer [*Kattsov et al.*, 2007]. The seasonality of the trend has been linked to the seasonality of the greenhouse warming, resulting in an increase of the surface atmospheric temperature [e.g., *Gillett et al.*, 2008].

Precipitation minus evapotranspiration over the Arctic terrestrial drainage system yields the amount of water available for runoff into the river networks that input to the Arctic Basin, excluding long-term soil moisture or groundwater storage. River discharge, and its time variations, remains poorly constrained from observations [e.g., *Bring et al.*, 2016], although efforts are ongoing to build climatological data sets of river runoff, which are, for instance, required as boundary forcing for ocean models [see *Whitefield et al.*, 2015, and references therein for a review of the different existing data sets]. Therefore, models are essential to achieve a consistent and representative estimate of the magnitude and spatial distribution of the ever-changing Arctic terrestrial water budget for both the contemporary and future time periods. *Holland et al.* [2007] found a reasonable agreement between the CMIP3 multimodel mean and observational estimates of the total runoff to the basin. Moreover, *Wu et al.* [2005] have used coupled climate models to detect and attribute an anthropogenic influence (via climate change) on increased Arctic river discharge over the 20th century. Using an intermediate complexity model (University of Victoria (UVic) ESM), *Nugent and Matthews* [2012] found that historic and projected high-latitude runoff increases (+32% between 1800 and 2100 in that model) can be attributed to both climate change (including increasing precipitation) and increased plant water use efficiency due to higher CO_2 levels. Their results highlight the role of vegetation and its response to both climate change and increases in Arctic terrestrial hydrologic change. Improved understanding and modeling of the amplitude of the water use efficiency effect and the vegetation community response to climate change are required to increase our confidence in terrestrial hydrologic projections (see further discussion in *Wrona et al.* [2016]).

In addition to net precipitation and river runoff, freshwater is also supplied to the Arctic Ocean from oceanic inflow. The largest oceanic source of freshwater is the flow through Bering Strait, which accounts for 2500–3500 km^3/yr (with respect to a reference salinity of 34.8 [*Serreze et al.*, 2006; *Woodgate et al.*, 2012]). The challenges associated with a proper representation of the flow through this narrow strait result in large discrepancies in the mean flow and its variability simulated by the different CMIP3 models [*Holland et al.*, 2007] as well as AOMIP ocean-sea ice models [*Clement-Kinney et al.*, 2014], despite their typical higher resolution than the climate models.

Loss of freshwater for the Arctic region occurs mostly through the export of sea ice and relatively fresh water masses along both sides of Greenland, through the CAA and Fram Strait. AOMIP hindcast sea ice-ocean models [*Jahn et al.*, 2012] and CMIP5 models [*Langehaug et al.*, 2013] have been shown to reproduce qualitatively well the observed mean sea ice export through Fram Strait, as well as the seasonal cycle and the interannual variability of this term. A model's performance at reproducing the sea ice export is mostly set by their ability to reproduce realistic sea ice thickness near Fram Strait and more generally in the Arctic Basin [*Wang et al.*, 2016]. Models have also been used to elucidate the mechanisms explaining the variability of the sea ice export. For instance, *Koeberle and Gerdes* [2003] have explored the sensitivity to atmospheric forcing (with an ocean-sea ice model) and shown that the year-to-year variability of the Fram Strait sea ice export is triggered by the variability of the wind over the eastern Arctic.

AOMIP hindcast sea ice-ocean models [*Jahn et al.*, 2012] as well as CMIP3 models [*Holland et al.*, 2007] show large discrepancies in their mean values of liquid freshwater export to the North Atlantic. Although the different AOMIP hindcasts exhibit large differences in their mean state, they are in better agreement regarding the seasonal cycle and the interannual variations of the freshwater export through the CAA and Fram Strait. The mechanisms driving the variability of the freshwater export are also consistent among most of the models: the variability of the liquid freshwater export through the CAA is driven by the volume flux anomalies, while both the salinity and velocity anomalies play a role for the variation of the freshwater export through Fram Strait [*Jahn et al.*, 2012; *Lique et al.*, 2009]. A better representation of the salinity field in the Arctic Basin appears to be crucial to improve robustness among models [*Jahn et al.*, 2012; *Wang et al.*, 2016].

Within the Arctic region, freshwater is stored in the forms of low-salinity water and sea ice in the ocean and snow, glaciers, groundwater [*Frappart et al.*, 2011], and permafrost ice [*Bosson et al.*, 2013; *Lee et al.*, 2014] over land. The computation of sea ice volume requires the knowledge of the sea ice thickness and concentration. *Stroeve et al.* [2012] have shown that CMIP3 and CMIP5 climate models are mostly consistent with sea ice extent observations, yet they tend to underestimate the trend observed over the past 30 years (although CMIP5 models present some improvement compared to CMIP3 models). The sea ice thickness and its variability, on the other hand, are less well constrained by observations and generally less well reproduced by coupled [*Kwok*, 2011; *Langehaug et al.*, 2013; *Stroeve et al.*, 2014] and forced models [*Jahn et al.*, 2012; *Gerdes and Koeberle*, 2007; *Johnson et al.*, 2012; *Wang et al.*, 2016]. The model deficiency regarding the representation of sea ice thickness has been related to biased sea ice drift [*Martin and Gerdes*, 2007; *Rampal et al.*, 2011] and related atmospheric circulation [*Stroeve et al.*, 2014], biased oceanic heat inflow from the North

Atlantic [*Gerdes and Koeberle*, 2007], and the lack of a representation of land fast ice [*Johnson et al*., 2012], among other factors.

The liquid freshwater content of the Arctic Ocean is often defined as the depth-integrated salinity referenced to 34.8 [*Aagaard and Carmack*, 1989], although the use of an arbitrary reference salinity may have negative attributes (see *Bacon et al*. [2016] and *Carmack et al.* [2015], for a discussion of problems related to this approach). The vertical stratification in the Arctic Basin, with a fresh halocline surface layer on top of the layer of water masses with roughly constant salinity, is often a difficult feature to simulate. Hence, the mean salinity profiles simulated in CMIP3 models (Figure 2) [*Holland et al*., 2007], as well as AOMIP ocean-sea ice hindcasts [*Holloway et al*., 2007; *Steiner et al*., 2004], are largely biased when compared to observation, resulting in large model-to-model and model-to-observation differences in the spatial pattern and the magnitude of the freshwater storage [*Jahn et al*., 2012; *Holland et al*., 2007]. Simulating a realistic stratification is challenging, as the model salinity structure of the water column has been shown to be sensitive to the level of background vertical mixing [*Zhang and Steele*, 2007], the implementation of parameterizations for example associated with highly localized sea ice-associated brine rejection [*Nguyen et al*., 2009], or the use of sea surface salinity restoring [*Steele et al*., 2001a], among other factors.

Although the mean freshwater content differs widely among the AOMIP models analyzed by *Jahn et al*. [2012], the time variability exhibits some robust features in the different models, with consistent decadal variability. This is not surprising as studies using simple barotropic models [e.g., *Proshutinsky and Johnson*, 1997] or forcing sensitivity experiments with ocean-sea ice models [*Zhang et al*., 2003; *Condron et al*., 2009; *Stewart and Haine*, 2013] have revealed that the phases of accumulation and release of liquid freshwater within the Beaufort Gyre in the Canadian Basin are driven by the variability of the large-scale atmospheric circulation (as discussed further by *Vihma et al.* [2016], and *Carmack et al.* [2015]). Hence, models forced with a prescribed atmosphere exhibit similar variability of the liquid freshwater storage [*Jahn et al*., 2012].

Seasonal Arctic terrestrial snow cover is another major component of the terrestrial cryosphere (see discussion in *Bring et al.* [2016]). It has important effects on climate due to its high albedo [e.g., *Lemke et al*., 2007]. *Brutel-Vuilmet et al*. [2013] found that, on average, CMIP5 models reproduce the observed Northern Hemisphere (NH) snow cover extent (SCE) quite well though there is a fairly large intermodel spread and the ensemble mean trend toward a reduced spring snow cover extent over the 1979–2005 period is underestimated. *Derksen and Brown* [2012] have also shown that late spring–early summer (May–June) NH snow cover, which is predominantly restricted to the high Arctic, decreased significantly over the last four decades and that the decrease in June SCE was greater than that simulated by an ensemble of eight CMIP5 models. Using the VIC model forced with gridded climatic observations, *Shi et al.* [2013] reproduced reasonably well the satellite-observed spatial and temporal variations of SCE and they found that both observed and modeled North American and Eurasian snow cover in the pan-Arctic have statistically significant negative trends from April through June over the period 1972–2006. Using an optimal fingerprinting technique to look for consistency in the temporal pattern of spring NH SCE between observations and simulations from 15 CMIP5 models, *Rupp et al*. [2013] concluded that the decline in observed NH SCE cannot be explained by natural forcing alone.

Over the past decades, mass loss of the GIS and Arctic glaciers [*Bamber et al*., 2012; see also *Bring et al*., 2016] and, to a limited extent, permafrost degradation [*Serreze et al*., 2002] have likely resulted in additional freshwater discharge to the Arctic Ocean. Better implementation of ice sheet and permafrost models into global climate models is required to quantify these contributions to the Arctic freshwater budget and their associated past and future changes.

3.2. Projected Changes and Key Drivers

Freshwater budgets for the Arctic Ocean have been analyzed for historical and projected conditions in a number of studies [e.g., *Miller and Russell*, 2000; *Holland et al*., 2006, 2007; *Arzel et al*., 2008; *Rawlins et al*., 2010; *Haine et al*., 2015]. These studies indicate an acceleration of the Arctic freshwater cycle, in that there is an increase in the flux of water passing through the hydrological elements. In particular, CMIP3 models simulate an increase in the net freshwater flux to the Arctic Ocean from enhanced river runoff, net precipitation, and net ice melt, which is in part compensated by an increase in liquid ocean freshwater transport to lower latitudes. This is consistent with analyses of simulated precipitation and evaporation over the Arctic Ocean and its terrestrial watershed [*Kattsov et al*., 2007; *Bengtsson et al*., 2011].

Table 1. Mean Annual Values in Millimeters From 41 Models Participating in CMIP5[a]

Term	Early 21st Century	Late 21st Century	Change
Net Precipitation (P − E)	211	259	48
Precipitation	332	451	119
Evaporation	121	191	70
Snowfall	216	205	−11

[a] Simulations using the RCP8.5 forcing scenario are used. Values are averaged over 70–90°N.

CMIP5 simulations also exhibit increases in net precipitation (Figure 4c) over the Arctic region north of 70°N (Table 1), with increases in precipitation (Figure 4a) being larger than those in evaporation or evapotranspiration (Figure 4b; see also discussion in *Vihma et al.* [2016]). CMIP5 models have been used to explore the relative role of local evaporation changes versus poleward moisture transport changes in driving a projected intensification of the Arctic water cycle and shown that over 50% of the projected Arctic precipitation increase by the late 21st century is related to local evaporation changes, closely tied to the retreat of sea ice [*Bintanja and Selten*, 2014]. Seasonally, the contribution due to local evaporation is largest in winter and the moisture transport largest in late summer and autumn.

Climate models robustly simulate an increase in poleward atmospheric moisture transport to the Arctic with future rising greenhouse gases [e.g., *Held and Soden*, 2006]. Changes in moisture transport can be driven by thermodynamical or dynamical influences. Thermodynamic effects are caused by increased atmospheric moisture content and a larger poleward moisture gradient, both of which lead to a larger poleward transport of moisture. As the climate warms, the poleward moisture gradient increases as humidity increases more rapidly at lower latitudes for a given temperature increase. Dynamical factors relate to changes in atmospheric circulation, for example, the number and strength of storms and associated frontal features (including atmospheric rivers). As discussed further in *Vihma et al.* [2016] and the references therein, model studies indicate that the majority of changes in polar moisture transport are thermodynamically driven with a smaller contribution from dynamical processes.

While Arctic precipitation increases in the 21st century, CMIP5 models simulate an overall reduction in snowfall for the Arctic region (Table 1). However, the annual mean masks large and nearly compensating seasonal changes (Figure 5) [see also *Hezel et al*., 2012], with reductions simulated in June–October, but increases during the winter months. Regardless of the wintertime increases in snowfall, snow depths on sea ice decline considerably over the 21st century in part because snow accumulation starts later due to the prolonged summer open water season [*Hezel et al*., 2012]. This has implications for insulation and albedo properties of the sea ice and relevant polar feedbacks.

Climate models predict that terrestrial Arctic snow conditions will change substantially over the 21st century [*Bring et al*., 2016]. Most models suggest that poleward of 75°N, winter snowfall, and precipitation more generally, will increase [e.g., *Brutel-Vuilmet et al*., 2013] with some regional variations. However, increased winter snowfall does not necessarily equate to more snow on the ground, as climate models project that the snow season will also shorten from both ends across most of the northern midlatitude and high latitude [*Räisänen*, 2008]. Due to these competing processes of more snowfall, a shorter snow accumulation season, and midwinter snowmelt, the March snow water equivalent signal exhibits a regionally mixed response, with projected increases in colder regions such as Siberia, northern Alaska, and northern Canada and decreases elsewhere.

Snow conditions strongly affect soil temperatures and consequently permafrost conditions due to the insulative properties of snow. Through a series of prescribed snow experiments, *Lawrence and Slater* [2010] showed that a shortening snow season enhances soil warming due to increased solar absorption. Meanwhile, a shallowing snowpack reduces soil warming due to weaker winter insulation from cold atmospheric air, as snow deepening has comparatively less impact due to saturation of snow insulative capacity at deeper snow depths. Snow depth and snow season length trends tend to be positively correlated, but their effects on soil temperature are opposing. Consequently, on the century timescale, the net change in snow state can amplify or mitigate soil warming (see also discussion in *Bring et al.* [2016], and effects on resources in *Instanes et al.* [2016]).

In terms of modeling runoff from the terrestrial Arctic drainage systems, most models project a stronger increase in precipitation than evapotranspiration, which results in increases in runoff in high-latitude basins

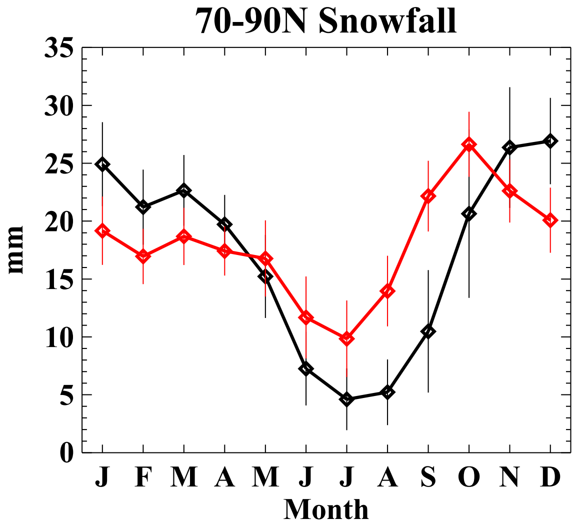

Figure 5. Multimodel averaged 70–90°N snowfall from CMIP5 models using the RCP8.5 forcing scenario. The red line represents values from the early 21st century (2006–2015 average) and the black line from the late 21st century (2085–2095). Forty-one models are used in the analysis, and the vertical bars represent the standard deviation across the different models.

[e.g., *Holland et al.*, 2006, 2007; *Mokhov et al.*, 2003]. The latest results from CMIP5 ensemble experiments have also shown that runoff increases are likely under most emission scenarios, consistent with the projected precipitation increases [*Collins et al.*, 2013]. Using future climate projections and a macroscale hydrological model, *Arnell* [2005] calculated increases of up to 31% in river inflows to the Arctic by the 2080s under high emissions and up to 24% under lower emissions, with large differences between climate models. He also demonstrated that future runoff projections using such an uncoupled model are more sensitive to the input data used to drive the models than to the terrestrial hydrologic model form and parameterization.

As noted previously, all of these estimates of increased river discharge to the Arctic Ocean derive from models that do not adequately represent permafrost dynamics and therefore are missing or incorrectly representing the impacts of permafrost state changes on soil hydrology and runoff. Permafrost dynamics in most of the CMIP5 models show large deficiencies which limit the value of direct diagnosis of present and future permafrost conditions [*Koven et al.*, 2012; *Slater and Lawrence*, 2013]. Projections of permafrost thaw in CCSM4, one of the better performing CMIP5 models with respect to permafrost processes, indicate the potential for severe reductions in near-surface permafrost extent by 2100 under RCP8.5 (9 million km^2, or 72% of the mean present-day conditions; [*Lawrence et al.*, 2012]). However, *Lawrence et al.* [2012] also note that the projected near-surface permafrost loss is only 43% relative to the present-day conditions when the contribution of biases in the simulated climate is accounted for (CCSM4 simulates too much snowfall across much of the Arctic leading to warm soil temperature biases). Most CMIP5 models do not accurately simulate permafrost conditions due to either climate biases or land model deficiencies or limitations [*Koven et al.*, 2013]. Consequently, *Slater and Lawrence* [2013] instead utilized indirect methods to diagnose current and future conditions suitable for permafrost and calculated the sensitivity of future permafrost extent to temperature change as -1.67 ± 0.7 million km^2/°C of terrestrial Arctic warming (Figure 6). The loss of permafrost, which as noted previously acts as a barrier to vertical flow and supports moist soil conditions near the surface, could open up deeper flow paths to the regional groundwater system. *Bense et al.* [2009, 2012], using a coupled hydrothermal model, found an increased groundwater contribution to streamflow after permafrost thaw. In the Community Land Model, permafrost thaw is followed by increased base flow and soil drying, even in the face of projected increases in precipitation minus evaporation. This Arctic soil drying trend is the largest simulated soil moisture trend found anywhere on the planet [*Lawrence et al.*, 2015].

Projections of Arctic land conditions from a large-scale climate model have also been used to inform other aspects of potential changes in the terrestrial hydrologic cycle. For example, *Prowse et al.* [2010], using air temperature change projections, suggested that Arctic rivers will experience a decrease in spring flooding because of lessening in the severity of ice jamming although changes in snowmelt may complicate the picture (see also *Bring et al.* [2016]). Additionally, *Dibike et al.* [2011] using a one-dimensional lake simulation model driven by output from a climate model indicated that future warming will result in an overall increase in lake water temperature, with summer stratification starting earlier and extending later into the year. This led to changes in the seasonal timing of lake freeze-up and breakup, with a resulting decrease in lake ice duration. Maximum lake ice thickness was also modeled to decrease by up to 25%.

Projected increases in Arctic Ocean freshwater from rivers and precipitation minus evaporation over the 21st century contribute to an increase in the net storage of freshwater within the Arctic Ocean. The rate of change is projected to grow over the 21st century, with a general freshening of the upper ocean layers, and a smaller

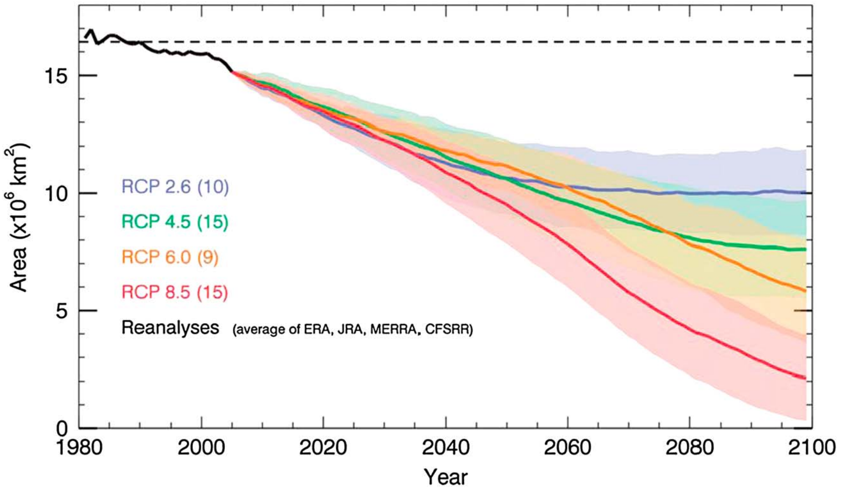

Figure 6. Projected change in a sustainable permafrost area. As most of the CMIP5 models do not include a representation of the permafrost, the projections are based on climate change from the present day via the surface frost index [*Nelson and Outcalt*, 1987] calculated with the model outputs. Shaded areas represent one standard deviation across the 13 CMIP5 models used in the analysis, and the dashed black line is the model equivalent present-day total area of permafrost. Figure reprinted from *Slater and Lawrence* [2013] (©American Meteorological Society. Used with permission).

but partially compensating decline in sea ice freshwater storage through ice volume reductions [*Haine et al*., 2015; *Carmack et al*., 2015]. Increasing ocean freshwater content is projected to increase sea surface height, particularly in the Canadian Basin [*Long and Perrie*, 2013].

The increasing sources of water to the Arctic are in part compensated by increases in freshwater export to the North Atlantic [e.g., *Holland et al*., 2007; *Vavrus et al*., 2012]. Oceanic export changes include contributions of both liquid water and sea ice across a number of straits, including the Bering Strait, Fram Strait, the Barents Sea Opening, and the complex channels of the CAA (Figure 3). The liquid flux changes have a contribution from both changing salinity and changing volume transport. The change in ice export flux is caused by changes in both ice velocity and ice thickness. In general, 21st-century simulations exhibit reductions in sea ice transport to the North Atlantic, which are more than compensated by increases in the liquid ocean transport [e.g., *Holland et al*., 2007; *Jahn and Holland*, 2013]. This change in the phase (liquid or solid) of the transport can have downstream implications as the ultimate fate of the water and its proximity to potentially sensitive deep-water formation regions can be affected. We return to this in section 4.

3.3. Uncertainty in Projections of Change

Models generally agree on the sign of many changes in the Arctic freshwater system and an overall acceleration of the Arctic hydrological cycle. However, they disagree considerably in the magnitude of simulated change. There are also appreciable model discrepancies and biases in the simulated mean state conditions [e.g., *Kattsov et al*., 2007, for precipitation; *Jahn et al*., 2012, for ocean salinity; *Brutel-Vuilmet et al*., 2013, for SCE]. The importance of mean climate biases for potential errors in the projected change in freshwater budget terms for the Arctic is uncertain. There is evidence that projected change in some quantities (e.g., precipitation, sea ice, and permafrost) is affected by the late 20th-century climatological conditions in coupled climate models [*Holland et al*., 2010; *Mahlstein and Knutti*, 2010; *Massonnet et al*., 2012; *Hodson et al*., 2013; *Lawrence et al*., 2012]. A better understanding of this for Arctic freshwater terms is needed to further understand uncertainty in future projections, provide guidance for model development needs, and constrain the likelihood of potential future change. This also has implications for resources in the region and the availability of reliable climate services.

As discussed by *Hawkins and Sutton* [2009], there are a number of sources of uncertainty in climate change projections. These include uncertainty arising from the models themselves (model structure), uncertainty from the influence of chaotic internal variability, and uncertainty associated with the future of greenhouse gas and other emissions. By comparing across a group of models that are run with consistent external forcing scenarios, the magnitude of these different sources of uncertainty for climate variables at different regional

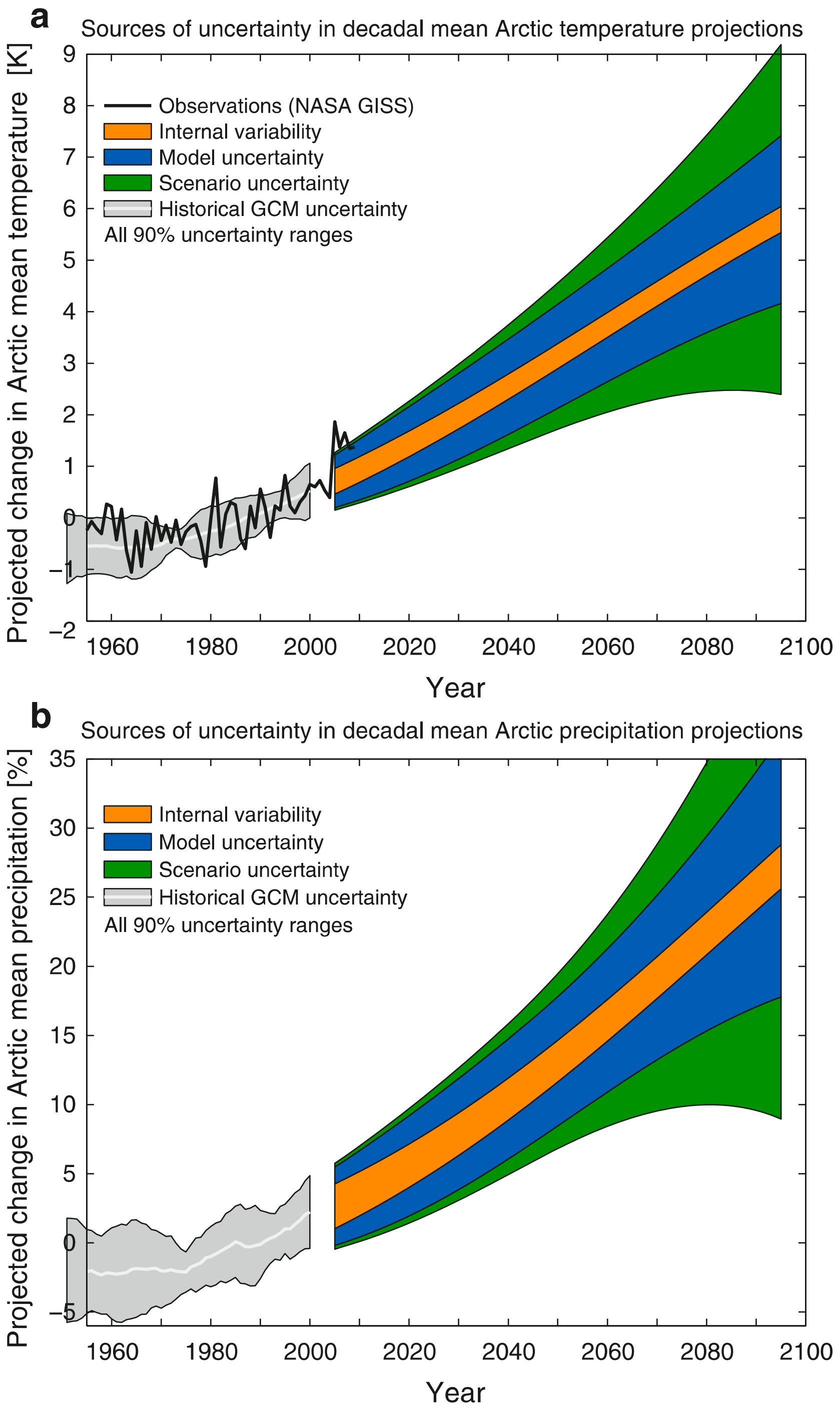

Figure 7. Sources of uncertainty in projections of Arctic (a) surface temperature and (b) precipitation change. Results are from CMIP3 models, using the method described in *Hawkins and Sutton* [2009]. Figure reprinted from *Hodson et al.* [2013].

domains can be estimated [*Hawkins and Sutton*, 2009]. As shown in Figure 7, taken from *Hodson et al.* [2013], Arctic temperature and precipitation projections exhibit changes in the relative importance of various sources of uncertainty over time. In the near term, the dominant uncertainty is associated with internal variability and there is a growing importance of the forcing (scenario) uncertainty in the longer term. Model uncertainty is important for all timescales. Similar general characteristics are found for other climate variables, such as projected Arctic sea ice extent change (Figure 8). Perturbed physics ensembles [e.g., *Murphy et al.*, 2004;

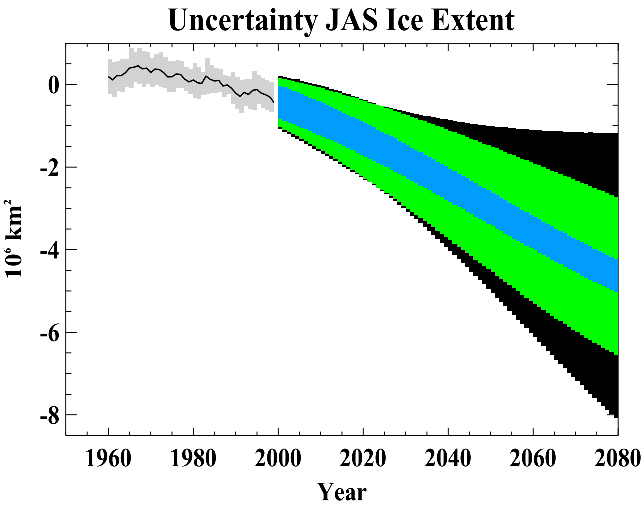

Figure 8. Magnitude of uncertainty as a function of time in projected change in July–August–September Northern Hemisphere sea ice extent from internal variability (blue), model structure (green), and forcing scenario (black). The change is relative to 2000 values, and results are from CMIP3 models. The method of *Hawkins and Sutton* [2009] is used to diagnose the uncertainty contributions.

Stainforth et al., 2005; *Collins et al.*, 2006; *Hodson et al.*, 2013] can provide further information on the importance of different parameterizations and parameter uncertainty for projected change.

Large ensemble simulations with a single climate model can provide additional insight on the uncertainty that arises from internal variability [e.g., *Deser et al.*, 2012; *Wettstein and Deser*, 2014; *Kay et al.*, 2015]. Internal variability is a fundamental property of the climate due to its chaotic system dynamics. An estimate of the uncertainty associated with internal variability is necessary in order to put time series from a short observational record into a broader context, for example, for questions of detection and attribution. Uncertainty estimates also provide useful insights on the limits of prediction that are inherent to the system and as such cannot be overcome through model improvements or improved observing networks and forecast initialization. This in turn can inform research and model development needs. An illustration of results from ensemble simulations is shown in Figure 9, where projections of the Fram Strait ice flux from the Community Earth System Model (CESM)-Community Atmosphere Model, Version 5 (CAM5) large ensemble [*Kay et al.*, 2015] are shown. This large ensemble includes 30 integrations from a single and identical climate model that are subject to the same external forcing for 1920–2100. The only difference in the simulations is a very small perturbation in their initial (1920) state. As such, differences across the ensemble members are solely due to internal variability within the simulated climate. Figure 9 indicates that while general projected declines occur in the transport of ice to the North Atlantic, even on a 20 year timescale in the 2000–2040 period, simulated increases are possible due to natural variability overwhelming the anthropogenically greenhouse gas forced trend. This illustrates the difficulty in using short observational records or single-model ensemble members to investigate changes in the Arctic system because it is subject to considerable natural variability. Quantifying the influence of natural variability, as is made possible through large ensemble simulations, is necessary if we are to better understand observed Arctic change.

Understanding the factors responsible for multimodel scatter in simulated Arctic change is important for refining projections and improving models. Simpler models can aid in this mechanistic understanding by allowing for the isolation of important processes of interest and providing a simpler framework for interpretation. As one example, *Hwang and Frierson* [2010] used an energy balance model to assess processes affecting uncertainty in moist static energy transport to the Arctic in CMIP3 models. This indicated that increases in atmospheric moisture were primarily responsible for projected moist static energy transport increases and that the spread in the models was associated with cloud-related radiation changes. This points to uncertainties in the models that are in need of further developments.

4. Using Models to Investigate the Impacts of Arctic Freshwater Change

The Arctic region, and its freshwater system, is one among other components of the Earth system. As such, changes affecting the Arctic freshwater system are likely to have significant impacts on the other components of the Earth system, at both regional and global scales [e.g., *Prowse et al.*, 2015a]. Global ESMs have been used to examine the consequences of changes affecting one component of the Arctic freshwater system on the global climate or the biochemistry within the Arctic region and beyond. As one example, climate models have been used to evaluate the potential impact of the decrease in Arctic sea ice extent for the

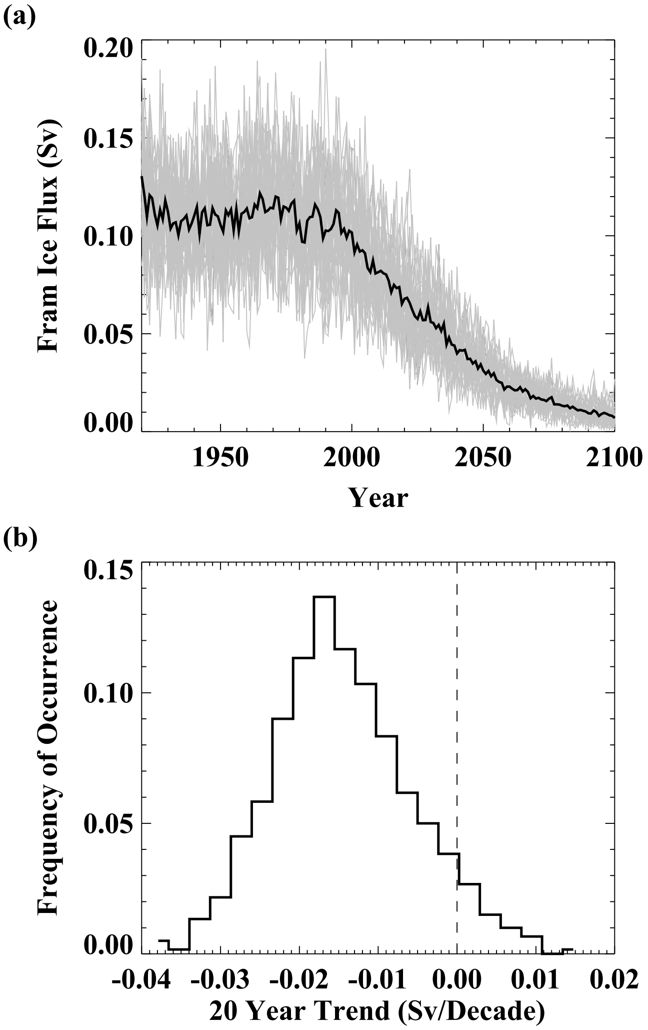

Figure 9. The Fram Strait ice transport simulated in the CESM-CAM5 large ensemble. (a) The ensemble mean (black) and 30 ensemble members (grey) time series from 1920 to 2100 in sievert. (b) The distribution of 20 year trends in sievert per decade during the 2000–2040 time period computed for all possible 20 year segments from the 30 ensemble members.

midlatitude climate and weather [e.g., *Deser et al.*, 2010]. In the following, we focus on two aspects of the Arctic freshwater system integration within the Earth system: the downstream impact of the change in Arctic freshwater export to lower latitudes and the implication of the Arctic freshwater changes for the global carbon cycle.

4.1. Downstream Effects of Freshwater Changes

Many of the modeling studies of the Arctic freshwater budget and its variability have been motivated by the idea that a small change of the Arctic freshwater export to the North Atlantic could modify the salinity of the surface layer in the subpolar region, including that in the convective region [*Aagaard and Carmack*, 1989; *Haak et al.*, 2003; *Karcher et al.*, 2005; *Carmack et al.*, 2015], and hence influence the dense water formation. This in turn could modulate the intensity of the AMOC [*Holland et al.*, 2001; *Rennermalm et al.*, 2007; *Arzel et al.*, 2008; *Jahn and Holland*, 2013] and associated oceanic heat transport.

Episodes of "Great Salinity Anomalies" observed in the North Atlantic over the past 50 years [e.g., *Belkin et al.*, 1998] have been used as test cases to understand the downstream impact of the Arctic freshwater exports. Modeling studies of *Koeberle and Gerdes* [2003] and *Haak et al.* [2003] have for instance shown that positive anomalies of sea ice export through Fram Strait propagate along the East Greenland Current and eventually drive a negative anomaly of the sea surface salinity in the Labrador Sea a year later. However, the effect of the salinity decrease or lack thereof on the intensity of the AMOC appears to be model dependent [*Häkkinen*, 1999; *Haak et al.*, 2003; *Olsen and Schmith*, 2007; *Jahn et al.*, 2010a].

As explained in section 3, the Arctic hydrological cycle is expected to amplify in a warming climate [*Bintanja and Selten*, 2014], which, combined with the seasonal disappearance of the sea ice, is projected to result in a modification of the Arctic freshwater export in the future. One might expect both an intensification of the exports [*Holland et al.*, 2007; *Jahn and Holland*, 2013] and a modification of the contribution of liquid freshwater versus sea ice and East versus West of Greenland [*Koenigk et al.*, 2007].

Rennermalm et al. [2007] used the low-resolution (3.6° longitude × 1.8° latitude) UVic intermediate complexity climate model to explore the response of the AMOC to a change of river runoff input in the Arctic Basin. They found a negative linear relationship between changes of the intensity of the AMOC and the river runoff input, the latter driving changes of the freshwater export to the North Atlantic. However, the low resolution of the model and its subsequent biases in the representation of the dense water formation prevented the authors from a detailed description of the mechanisms at play to link the changes of river input and the AMOC intensity.

Using a climate model with higher resolution (about 1° longitude × 0.5° latitude for the ocean component) forced with a different greenhouse gas emission scenario, *Jahn and Holland* [2013] have been able to investigate in detail the potential future impact of the freshwater export on the AMOC and in particular to examine separately the contributions of the different dense water formation sites. They found that the only significant correlation between the sea surface salinity in a convective basin and the freshwater outflow is between the Labrador Sea and the liquid freshwater export through Fram Strait, which confirms the finding of *Häkkinen* [1999]. They also found that, despite the geographical vicinity, the changes of freshwater export through the CAA have little effect on the deep convection in the Labrador Sea, as most of the freshwater stays in the boundary current and does not reach the interior where convection occurs. This is consistent with the observational study of *Vage et al*. [2009], who found that a period of intensified deep convection in the Labrador Sea coincided with a period of increased freshwater export through Davis Strait. The study of *Jahn and Holland* [2013] thus underlines the importance of simulating realistically the different regions of deep convection (and their relative contribution to the deeper limb of the AMOC) to obtain a credible projection on the effect of increased Arctic freshwater outflow on the intensity of the AMOC.

Under a warming climate, an additional freshwater input to the North Atlantic might come from the GIS. Future projections suggest that this additional source of freshwater could alter the deep convection, resulting in a weakening of the AMOC [e.g., *Swingedouw et al*., 2014]. However, modeling and analytical studies have also suggested that enhanced GIS discharge might modify the dynamics of the outflow through the CAA (through a modification of the sea surface height gradient) and hence limit the export of freshwater on the western side of Greenland [*Rudels*, 2011].

4.2. Arctic Freshwater Influences on Biogeochemistry and the Carbon Cycle

Changes in the Arctic freshwater system have implications for biogeochemistry both on land [*Wrona et al*., 2016], where large and potentially vulnerable carbon stocks are currently frozen in permafrost, and in the ocean [*Carmack et al*., 2015]. With the transition to ESMs, biogeochemical processes and interactions are increasingly being incorporated into large-scale models. As discussed by *Vancoppenolle et al*. [2013], while ESMs agree on mechanisms of change in Arctic marine primary productivity over the 21st century, they disagree on the overall sign of change. This disagreement is due to different levels of compensation within the models of the effects of increased light availability, associated with sea ice cover decline, and increased nutrient limitation, associated with a more stable surface ocean and shoaling mixed layers. Reducing the uncertainty in projections of Arctic marine productivity requires improved biogeochemistry processes within the models. As one example, current models generally neglect nutrient fluxes from rivers. Model improvements also require enhanced observations to further constrain the simulations and inform model process development. The spatial scales of interest are also problematic as biological productivity often occurs at scales that are subgrid scale within large-scale climate models. Efforts to better account for spatial heterogeneity in simulated flux fields should also be pursued, as for instance regarding shortwave radiation in ice-covered waters [*Long et al*., 2015].

For the terrestrial system, vast quantities of carbon are currently frozen in permafrost soils (see discussion in *Wrona et al.* [2016]). Experimental studies suggest that as permafrost thaws, the newly unfrozen carbon may start to decompose, releasing potentially large amounts of CO_2 and methane to the atmosphere. Based on terrestrial carbon cycle models, initial projections of the amplitude of what is known as the permafrost-carbon feedback are beginning to emerge [*Schaefer et al*., 2014; *Koven et al*., 2015]. Yet the uncertainty associated with the estimates of carbon loss are large, with values ranging between 162 and 288 Pg C lost to the atmosphere by 2100 under RCP8.5 in the different CMIP5 models [*Schuur et al*., 2013]. This reflects the relatively poor level of both process understanding in these systems and cold region process representation in terrestrial carbon models [*Schuur et al*., 2015]. Carbon emissions due to permafrost thaw remain one of the least constrained biospheric feedbacks to climate [*IPCC*, 2013]. Soil hydrological conditions play a strong role in the decomposition process with drier soils generally leading to enhanced decomposition and CO_2 emissions while the thawing of saturated soils can enhance methane emissions. Methane emission processes are being incorporated into global LSMs [e.g., *Riley et al*., 2011; *Wania et al*., 2010] but are difficult to constrain. A critical additional question is whether the terrestrial Arctic landscape will become wetter or drier under climate change (see discussion in *Bring et al.* [2016]). Lastly, new methods to represent abrupt permafrost thaw and thermokarst need to be developed. Many of these abrupt thaw processes are directly related to and affect local hydrological conditions [*Jorgenson et al*., 2013] with implications for terrestrial biogeochemistry.

5. Major Knowledge Gaps and Future Research Directions

Climate models have some significant biases in representing the state of the Arctic, and in particular its freshwater system. Historically, the scarcity and the uncertainties of the observations in the Arctic region have made difficult any validation and calibration of the modeled state of the Arctic. The lack of observations has also hampered our ability to understand and quantify all the processes at play that need to be included in models. For instance, as discussed further in *Vihma et al*. [2016], large uncertainties remain associated with snowfall and rainfall measurements due to the gauge undercatch of solid precipitation, the low precipitation amounts, and the sparsely distributed observation stations, mostly biased toward low elevations and coastal regions among other factors. These uncertainties make it difficult to obtain a pan-Arctic estimate of the net precipitation, and even more difficult to estimate the temporal variations of this term [*Serreze and Hurst*, 2000; *Adam and Lettenmaier*, 2003; *Yang et al*., 2005]. One consequence is that the development and validation of LSMs that rely on precipitation as a critical input remain extremely challenging. More generally, building better observational data sets is crucial to improve the representation of all the aspects of the Arctic freshwater system in models. Indeed, it is necessary to obtain more accurate initial conditions for model predictions, to enhance the number of available data that can be assimilated for reliable reanalysis products, and to inform the validation of the different components of the climate models. It is also crucial to increase the spatial resolution of these observational data sets (or observation-based data sets like the atmospheric reanalyses), as such fields are used as boundary conditions for component models, which can be run at much higher resolutions than the existing data sets.

There have been some recent improvements following the impulse given by the International Polar Year (2007–2009) during which intensive measurement campaigns have been conducted. Additional valuable information is provided by satellite remote sensing, with the launch of several satellites that provide pan-Arctic estimates of different key parameters to quantify the different terms of the Arctic freshwater budget. As one example, observations from the Gravity Recovery and Climate Experiment satellite mission have been used to estimate the liquid freshwater content of the Arctic Ocean [*Morison et al*., 2012], the sea ice thickness [*Forsberg and Skourup*, 2005], the terrestrial water budget in the Eurasian Arctic [*Landerer et al*., 2010], and the mass loss of the GIS [*Chen et al*., 2006]. Such efforts will need to be maintained over long time periods in order to quantify the time variability of the observed parameters. Intense and coordinated observational activities will be carried out in the near future (2017–2019) as part of the Year of Polar Prediction (http://www.polarprediction.net/yopp.html).

Specific observations are also required for the development of improved numerical models. There is a strong need for process-oriented observations, which would help to better understand the interactions and feedbacks between the different components of the Arctic freshwater system. Two multidisciplinary observational programs (Surface Heat Budget of the Arctic Ocean (SHEBA) in the 1990s [*Uttal et al*., 2002] and the planned future Multidisciplinary Drifting Observatory for the Study of Arctic Climate (MOSAIC) field campaign—http://www.mosaicobservatory.org) have been designed to understand the interactions between the atmosphere, the ocean, and the sea ice in the Arctic region. SHEBA resulted in a better understanding of the dynamic and thermodynamic interplays between the atmosphere, ocean, and sea ice conditions. Findings from SHEBA have also been very influential on the treatment of sea ice and both the atmospheric and oceanic boundary layers in climate models [e.g., *Tjernström et al*., 2005]. Similar initiatives need to be undertaken in the future to better understand and quantify the cross-component interactions that need to be included in the climate models.

Conversely, model simulation can be used to help the design of future observing systems of the Arctic freshwater system. As one example, *Lindsay and Zhang* [2006] have used statistical methods applied to model outputs to determine the optimal location where a mooring should be deployed in the Arctic Basin, in order to monitor as best as possible the basin-wide mean ice thickness as well as the spatial and temporal patterns of variability. Advanced techniques like Observing System Simulation Experiments [*Biancamaria et al*., 2011] or adjoint-based systems [*Kauker et al*., 2009; *Heimbach et al*., 2010] are powerful tools to assess added value of planned or hypothetical observing systems and should be used more extensively in the future to best plan the future observing systems in the Arctic.

Besides building on the improving observational coverage in the Arctic region, a better evaluation of models is also needed. Innovative strategies are required to facilitate the comparisons between model and observations. There are difficulties with these comparisons in part due to discrepancies in the spatial scales of in situ observations relative to model fields and in part due to inconsistent definitions of remotely sensed and model-derived fields. The development of satellite simulators for climate models (where model output mimics exactly the information provided by satellite algorithms) is a promising development for more robust observational comparisons. This method has been used to better understand a climate model bias regarding the simulation of clouds in the Arctic region [*Cesana et al*., 2012]. As noted in *Carmack et al.* [2015], geochemical tracers provide an effective way to investigate the disposition and storage of freshwater in the Arctic. As such, the use of tracer-enabled ocean simulations, which for example incorporate tracers for different ocean freshwater sources [e.g., *Newton et al*., 2008; *Jahn et al*., 2010b] or for geochemical constituents, can provide a novel means to compare modeled and observed fields.

Model intercomparisons provide a method to better understand common biases within the simulated Arctic freshwater system and help inform model development needs. A full assessment of the Arctic freshwater budget in the CMIP5 simulations still needs to be carried out (similar to the analysis made by *Holland et al*. [2007] for the CMIP3 models), and a better understanding of the model deficiencies and biases regarding the mean state and the variability is required to gain confidence in the future projections of the Arctic freshwater system. Moreover, internal variability seen in model simulations needs to be better quantified and understood, as it might explain a significant part of the CMIP model spread and the discrepancy of individual model simulations with observations [*Kay et al*., 2015]. One way forward is the realization of a large ensemble of simulations such as that completed for the Community Earth System model [*Kay et al*., 2015]. Similar large ensembles should be performed with different climate models to better determine the role of internal variability within the context of forced anthropogenic change across numerous modeling systems.

Significant knowledge gaps remain regarding our understanding of the important processes explaining the variability of the different terms of the Arctic freshwater budget, or the feedbacks between the different components of the Arctic system. However, many important processes have been observed, quantified, or understood through process model studies, and more effort needs to be done to include these processes in climate models, through a direct representation or the development of parameterizations. For instance, while there is substantial progress in understanding important cold region terrestrial processes (e.g., sublimation from blowing snow, permafrost degradation and surface storage in lakes and wetlands, and infiltration in frozen soils), there is a lag in upscaling and incorporating the latest process understanding into the land surface components of global and regional climate models. The long-term impact of permafrost thaw on local and regional hydrology remains poorly understood but is absolutely critical in terms of predicting future Arctic soil moisture states and river discharge and associated changes in biogeochemical cycling. It is known that fine-scale processes such as thermokarst and thermal erosion affect local hydrologic conditions, but the ability to both predict when and where thermokarst and thermal erosion will occur and understand the large-scale hydrologic impact of these landscape geomorphic processes is poor. Other factors, such as the heat flux associated with riverine input to the Arctic Basin, have been shown to have large effects on the sea ice pack and the oceanic conditions [*Whitefield et al*., 2015]. However, ESMs do not yet simulate river runoff heat content. Most of the current state-of-the-art climate models also still lack an explicit representation of ice sheets and glaciers (and thus of the interactions and feedbacks between the GIS or other Arctic glaciers and the atmosphere, ocean, and sea ice), although predicting Greenland and other glaciers mass loss is crucial for sea level rise projections. Modeling the Arctic freshwater system is challenging in part due to the important feedbacks between the different components. Future model development toward increased complexity should allow a better understanding and quantification of these feedbacks.

6. Conclusion

The functioning of the Arctic freshwater system involves processes within numerous Earth system components and the interactions among those components. Variability and change in the Arctic hydrological system can have far-reaching effects on ocean circulation, sea level rise, and biogeochemical cycles with considerable climate implications. This motivates the need for a deeper understanding of the factors that determine system behavior and the impacts of that behavior.

Modeling systems are a powerful tool that, through appropriate experimental design and analysis, can be used to better understand many aspects of the Arctic freshwater system. As discussed here, a hierarchy of models that include different levels of complexity and coupled interactions allows us to investigate relevant processes and the large-scale effects of those processes on the water system. By designing appropriate experiments, numerical models can serve as a "virtual laboratory" and allow for hypothesis testing relevant to the freshwater system. Studies of this type have resulted in new insights into the processes and interactions of importance for the Arctic freshwater system. As more coupled interactions are incorporated into large-scale Earth system models, such as those related to biogeochemical cycles and ice sheet components, model experiments will provide a means to investigate the new feedbacks that arise.

Models also provide us with a predictive capability to determine how the system will evolve in the future, for example, in response to rising greenhouse gases. Model projections suggest a warmer and wetter Arctic in the future with a more vigorous hydrological cycle. Further work is needed to more clearly understand the factors that contribute to this change on various spatial and temporal scales and to investigate the climate system implications. Also, while the sign of the large-scale long-term change is quite consistent across models, there remains considerable uncertainty in the projected magnitude of change. In the near term (about a decade), this uncertainty is dominated by internal variability of the climate system, whereas in the longer term, model structure becomes the dominant uncertainty source.

The prediction uncertainty associated with model structure indicates a need to further improve model processes. Model development work is ongoing and has led to improvements that influence the Arctic freshwater cycle, such as those associated with cold region hydrology [e.g., *Swenson et al*., 2012]. Model development work is also targeting the incorporation of new processes within global Earth system models. This includes the incorporation of new components, such as interactive ice sheet models [e.g., *Lipscomb et al*., 2013], and the inclusion of new feedbacks and interactions within existing components, such as work to incorporate enhanced biogeochemical cycles in the land [e.g., *Koven et al*., 2015] and ocean [e.g., *Vancoppenolle et al*., 2013]. These new model capabilities have the potential to increase projection uncertainty by introducing new feedbacks and interactions that may not be very well constrained. However, they also allow for the investigation of the role of these new processes in Arctic freshwater variability and change and ultimately provide a means to better understand the complex and interactive Arctic system.

For continued progress in the use of models to understand the Arctic freshwater system, model validation, model development, and model experimental design activities are needed. This includes the use of innovative strategies, such as the incorporation of satellite simulators within climate models [e.g., *Bodas-Salcedo et al*., 2011], to better compare remotely sensed and simulated fields. It also requires further model development efforts and the more efficient transfer of knowledge gained in the observational and process modeling community into parameterization developments for large-scale models. Finally, the design of community experiments, such as those undertaken by the Coupled Model Intercomparison Project, has been an important resource to better understand the sources of projection uncertainty and common biases within models. This can in turn provide guidance on future model development needs. Model intercomparison studies designed to address feedbacks associated with the Arctic freshwater system should be considered for future activities.

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References

Aagaard, K., and E. C. Carmack (1989), The role of sea ice and other fresh water in the Arctic circulation, *J. Geophys. Res.*, *94*(C10), 14,485–14,498, doi:10.1029/JC094iC10p14485.

Adam, J. C. and D. P. Lettenmaier (2003), Adjustment of global gridded precipitation for systematic bias, *J. Geophys. Res.*, *108*(D9), 4257, doi:10.1029/2002JD002499.

Alexeev, V. A., D. J. Nicolsky, V. E. Romanovsky, and D. M. Lawrence (2007), An evaluation of deep soil configurations in the CLM3 for improved representation of permafrost, *Geophys. Res. Lett.*, *34*, L09502, doi:10.1029/2007GL029536.

Anderson, L. G., E. P. Jones, and B. Rudels (1999), Ventilation of the Arctic Ocean estimated by a plume entrainment model constrained by CFCs, *J. Geophys. Res.*, *104*, 13,423–13,429, doi:10.1029/1999JC900074.

Arnell, N. W. (2005), Implications of climate change for freshwater inflows to the Arctic Ocean, *J. Geophys. Res.*, *110*, D07105, doi:10.1029/2004JD005348.

Arzel, O., T. Fichefet, H. Goosse, and J.-L. Dufresne (2008), Causes and impacts of changes in the Arctic freshwater budget during the twentieth and twenty-first centuries in an AOGCM, *Clim. Dyn.*, *30*, 37–58, doi:10.1007/s00382-007-0258-5.

Bacon, S., Y. Aksenov, S. Fawcett, and G. Madec (2016), Arctic mass, freshwater and heat fluxes: Methods, and modelled seasonal variability, *Philos. Trans. R. Soc.*, *373*, 2052.

Bamber, J., M. van den Broeke, J. Ettema, J. Lenaerts, and E. Rignot (2012), Recent large increases in freshwater fluxes from Greenland into the North Atlantic, *Geophys. Res. Lett.*, *39*, L19501, doi:10.1029/2012GL052552.

Belkin, I. M., S. Levitus, J. Antonov, and S.-A. Malmberg (1998), "Great Salinity Anomalies" in the North Atlantic, *Prog. Oceanogr.*, *41*, 1–68.

Benestad, R. E., E. J. Førland, and I. Hanssen-Bauer (2002), Empirically downscaled temperature scenarios for Svalbard, *Atmos. Sci. Lett.*, *3*(2–4), 71–93.

Bengtsson, L., K. I. Hodges, S. Koumoutsaris, M. Zahn, and N. Keenlyside (2011), The changing atmospheric water cycle in polar regions in a warmer climate, *Tellus A*, *63*(5), 907–920.

Bense, V., G. Ferguson, and H. Kooi (2009), Evolution of shallow groundwater flow systems in areas of degrading permafrost, *Geophys. Res. Lett.*, *36*, L22401, doi:10.1029/2009GL039225.

Bense, V., H. Kooi, G. Ferguson, and T. Read (2012), Permafrost degradation as a control on hydrogeological regime shifts in a warming climate, *J. Geophys. Res.*, *117*, F03036, doi:10.1029/2011JF002143.

Beszczynska-Möller, A., R. A. Woodgate, C. Lee, H. Melling, and M. Karcher (2011), A synthesis of exchanges through the main oceanic gateways to the Arctic Ocean, *Oceanography*, *24*(3), 82–99, doi.10.5670/oceanog.2011.59.

Bhatt, U. S., et al. (2014), Implications of Arctic sea ice decline for the Earth system, *Ann. Rev. Environ. Resour.*, *39*, 57–89.

Biancamaria, S., et al. (2011), Assimilation of virtual wide swath altimetry to improve Arctic river modeling, *Remote Sens. Environ.*, *115*(2), 373–381.

Bintanja, R., and F. M. Selten (2014), Future increases in Arctic precipitation linked to local evaporation and sea-ice retreat, *Nature*, *509*, 479–482.

Blanchard-Wrigglesworth, E., and C. M. Bitz (2015), Characteristics of Arctic sea-ice thickness variability in GCMs, *J. Clim.*, *27*, 8244–8258, doi:10.1175/JCLI-D-14-00345.1.

Bodas-Salcedo, A., et al. (2011), COSP: Satellite simulation software for model assessment, *Bull. Am. Meteorol. Soc.*, *92*, 1023–1043, doi:10.1175/2011BAMS2856.1.

Bosson, E., J.-O. Selroos, M. Stigsson, L.-G. Gustafsson, and G. Destouni (2013), Exchange and pathways of deep and shallow groundwater in different climate and permafrost conditions using the Forsmark site, Sweden, as an example catchment, *Hydrogeol. J.*, *21*(1), 225–237.

Bowling, L. C., D. P. Lettenmaier, and B. V. Matheussen (2000), Hydroclimatology of the Arctic drainage basin, in *The Freshwater Budget of the Arctic Ocean*, edited by E. L. Lewis et al., pp. 57–90, Springer, New York.

Bowling, L. C., D. L. Kane, R. E. Gieck, L. D. Hinzman and D. P. Lettenmaier (2003), The role of surface storage in a low-gradient arctic watershed, *Water Resour. Res.*, *39*(4), 1087, doi:10.1029/2002WR001466.

Bowling, L. C., J. W. Pomeroy, and D. P. Lettenmaier (2004), Parameterization of blowing-snow sublimation in a macroscale hydrology model, *J. Hydrometeorol.*, *5*, 745–762.

Bring, A., and G. Destouni (2009), Hydrological and hydrochemical observation status in the pan-Arctic drainage basin, *Polar Res.*, *28*, 327–338, doi:10.1111/j.1751-8369.2009.00126.x.

Bring, A., and G. Destouni (2014), Arctic climate and water change: Model and observation relevance for assessment and adaptation, *Surv. Geophys.*, *35*, 853–877, doi:10.1007/s10712-013-9267-6.

Bring, A., I. Fedorova, Y. Dibike, L. Hinzman, J. Mård, S. H. Mernild, T. Prowse, O. Semenova, S. L. Stuefer, and M.-K. Woo (2016), Arctic terrestrial hydrology: A synthesis of processes, regional effects, and research challenges, *J. Geophys. Res. Biogeosci.*, *121*, doi:10.1002/2015JG003131.

Brutel-Vuilmet, C., M. Ménégoz, and G. Krinner (2013), An analysis of present and future seasonal Northern Hemisphere land snow cover simulated by CMIP5 coupled climate models, *Cryosphere*, *7*, 67–80, doi:10.5194/tc-7-67-2013.

Byrkjedal, O., J. Esau, and N. Gunnar Kvamsto (2008), Sensitivity of simulated wintertime Arctic atmosphere to vertical resolution in the ARPEGE/IFS model, *Clim. Dyn.*, *30*, 687–701.

Carmack, E., et al. (2015), Freshwater and its role in the Arctic Marine System: Sources, disposition, storage, export, and physical and biogeochemical consequences in the Arctic and global oceans, *J. Geophys. Res. Biogeosci.*, *120*, doi:10.1002/2015JG003140.

Cesana, G., and H. Chepfer (2012), How well do climate models simulate cloud vertical structure? A comparison between CALIPSO-GOCCP satellite observations and CMIP5 models, *Geophys. Res. Lett.*, *39*, L20803, doi:10.1029/2012GL053153.

Cesana, G., J. E. Kay, H. Chepfer, J. M. English and G. Boer (2012), Ubiquitous low-level liquid-containing Arctic clouds: New observations and climate model constraints from CALIPSO-GOCCP, *Geophys. Res. Lett.*, *39*, L20804, doi:10.1029/2012GL053385.

Charlton-Perez, A. J., et al. (2013), On the lack of stratospheric dynamical variability in low-top versions of the CMIP5 models, *J. Geophys. Res. Atmos.*, *118*, 2494–2505, doi:10.1002/jgrd.50125.

Chen, J. L., C. R. Wilson, and B. D. Tapley (2006), Satellite gravity measurements confirm accelerated melting of Greenland ice sheet, *Science*, *313*(5795), 1958–1960.

Clement-Kinney, J., W. Maslowski, Y. Aksenov, B. de Cuevas, A. Nguyen, R. Osinski, M. Steele, R. Woodgate, and J. Zhang (2014), On the flow through Bering Strait: A synthesis of model results and observations, in *The Pacific-Arctic Region: Ecosystem Status and Trends in a Rapidly Changing Environment*, edited by J. Grebmeier, pp. 167–198, Springer, Netherlands.

Collins, B., et al. (2011), Development and evaluation of an Earth-system model-HadGEM2, *Geosci. Model Dev.*, *4*(4), 1051–1075, doi:10.5194/gmd-4-1051-2011.

Collins, M., B. B. Booth, G. R. Harris, J. M. Murphy, D. M. Sexton, and M. J. Webb (2006), Towards quantifying uncertainty in transient climate change, *Clim. Dyn.*, *27*(2–3), 127–147.

Collins, M., et al. (2013), Long-term climate change: Projections, commitments and irreversibility, in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by T. F. Stocker, Cambridge Univ. Press, Cambridge, U. K., and New York.

Comiso, J. C., D. J. Cavalieri, C. L. Parkinson, and P. Gloersen (1997), Passive microwave algorithms for sea ice concentration: A comparison of two techniques, *Remote Sens. Environ.*, *60*(3), 357–384.

Condron, A., P. Winsor, C. Hill, and D. Menemenlis (2009), Simulated response of the Arctic freshwater budget to extreme NAO wind forcing, *J. Clim.*, *22*, 2422–2437, doi:10.1175/2008JCLI2626.1.

Cullather, R. I., and M. G. Bosilovich (2012), The energy budget of the polar atmosphere in MERRA, *J. Clim.*, *25*(1), 5–24.

Danabasoglu, G., W. G. Large, and B. P. Briegleb (2010), Climate impacts of parameterized Nordic Sea overflows, *J. Geophys. Res.*, *115*, C11005, doi:10.1029/2010JC006243.

Dankers, R., E. J. Burke, and J. Price (2011), Simulation of permafrost and seasonal thaw depth in the JULES land surface scheme, *Cryosphere*, *5*, 773–790, doi:10.5194/tc-5-773-2011.

Davis, P. E. D., C. Lique, and H. L. Johnson (2014), On the link between Arctic sea ice decline and the freshwater content of the Beaufort Gyre: Insights from a simple process model, *J. Clim.*, *27*, 8170–8184, doi:10.1175/JCLI-D-14-00090.1.

de Boer, G., W. D. Collins, S. Menon, and C. N. Long (2011), Using surface remote sensors to derive radiative characteristics of mixed-phase clouds: An example from M-PACE, *Atmos. Chem. Phys.*, *11*, 11,937–11,949, doi:10.5194/acp-11-11937-2011.

Dee, D. P., et al. (2011), The ERA-Interim reanalysis: Configuration and performance of the data assimilation system, *Q. J. R. Meteorol. Soc.*, *137*, 553–597, doi:10.1002/qj.828.

Derksen, C., and R. Brown (2012), Spring snow cover extent reductions in the 2008–2012 period exceeding climate model projections, *Geophys. Res. Lett.*, *39*, L19504, doi:10.1029/2012GL053387.

Deser, C., R. Tomas, M. Alexander, and D. Lawrence (2010), The seasonal atmospheric response to projected Arctic sea ice loss in the late 21st century, *J. Clim.*, *23*, 333–351, doi:10.1175/2009JCLI3053.1.

Deser, C., A. Phillips, V. Bourdette, and H. Teng (2012), Uncertainty in climate change projections: The role of internal variability, *Clim. Dyn.*, *38*, 527–547.

Dibike, Y. B., P. Gachon, A. St-Hilaire, T. B. M. J. Ouarda, and V. T. V. Nguyen (2008), Uncertainty analysis of statistically downscaled temperature and precipitation regimes in Northern Canada, *Theor. Appl. Climatol.*, *91*(1–4), 149–170.

Dibike, Y., T. Prowse, T. Saloranta, and R. Ahmed (2011), Response of Northern Hemisphere lake-ice cover and lake-water thermal structure patterns to a changing climate, *Hydrol. Processes*, *25*, 2942–2953, doi:10.1002/hyp.8068.

Dunne, J. P., et al. (2012), GFDL's ESM2 global coupled climate-carbon Earth system models. Part I: Physical formulation and baseline simulation characteristics, *J. Clim.*, *25*(19), 6646–6665.

Ekici, A., C. Beer, S. Hagemann, and C. Hauck (2013), Improved soil physics for simulating high latitude permafrost regions by the JSBACH terrestrial ecosystem model, *Geosci. Model Dev. Discuss.*, *6*(2), 2655–2698.

Emery, W., C. Fowler, and J. Maslanik (1995), Satellite remote sensing of ice motion, in *Oceanographic Applications of Remote Sensing*, edited by M. Ikeda and F. W. Dobson, CRC Press, Boca Raton, Fla.

Euskirchen, E. S., et al. (2006), Importance of recent shifts in soil thermal dynamics on growing season length, productivity, and carbon sequestration in terrestrial high-latitude ecosystems, *Global Change Biol*, *12*, 731–750, doi:10.1111/j.1365-2486.2006.01113.x.

Feltham, D. L., N. Untersteiner, J. S. Wettlaufer, and M. G. Worster (2006), Sea ice is a mushy layer, *Geophys. Res. Lett.*, *33*, L14501, doi:10.1029/2006GL026290.

Finnis, J., J. Cassano, M. M. Holland, M. C. Serreze, and P. Uotila (2009), Synoptically forced hydroclimatology of major Arctic watersheds in general circulation models, Part 1: The Mackenzie River Basin, *Int. J. Clim.*, *29*(9), 1226–1243.

Flocco, D., D. Schroder, D. L. Feltham, and E. C. Hunke (2012), Impact of melt ponds on Arctic sea ice simulations from 1990 to 2007, *J. Geophys. Res.*, *117*, C09032, doi:10.1029/2012JC008195.

Forsberg, R., and H. Skourup (2005), Arctic Ocean gravity, geoid and sea-ice freeboard heights from ICESat and GRACE, *Geophys. Res. Lett.*, *32*, L21502, doi:10.1029/2005GL023711.

Fowler, H. J., S. Blenkinsop, and C. Tebaldi (2007), Linking climate change modelling to impacts studies: Recent advances in downscaling techniques for hydrological modeling, *Int. J. Climatol.*, *27*(12), 1547–1578.

Frampton, A., S. L. Painter, and G. Destouni (2013), Permafrost degradation and subsurface-flow changes caused by surface warming trends, *Hydrogeol. J.*, *21*(1), 271–280, doi:10.1007/s10040-012-0938-z.

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

Frappart, F., G. Ramillien, and J. S. Famiglietti (2011), Water balance of the Arctic drainage system using GRACE gravimetry products, *Int. J. Remote Sens.*, *32*(2), 431–453, doi:10.1080/01431160903474954.

Gerdes, R., and C. Koeberle (2007), Comparison of Arctic sea ice thickness variability in IPCC Climate of the 20th century experiments and in ocean-sea ice hindcasts, *J. Geophys. Res.*, *112*, C04S13, doi:10.1029/2006JC003616.

Gerdes, R., M. Karcher, C. Koberle, and K. Fieg (2008), Simulating the long-term variability of liquid freshwater export from the Arctic Ocean, in *Arctic-Subarctic Ocean Fluxes*, edited by R. R. Dickson, J. Meinke, and P. Rhines, pp. 405–425, Springer, Netherlands.

Gillett, N. P., D. A. Stone, P. A. Stott, T. Nozaw, A. Y. Karpechko, G. C. Hegerl, M. F. Wehner, and P. D. Jones (2008), Attribution of polar warming to human influence, *Nat. Geosci.*, *1*(11), 750–754.

Giorgetta, M. A., et al. (2013), Climate and carbon cycle changes from 1850 to 2100 in MPI-ESM simulations for the Coupled Model Intercomparison Project phase 5, *J. Adv. Model. Earth Syst.*, *5*, 572–597, doi:10.1002/jame.20038.

Goosse, H., T. Fichefet, and J.-M. Campin (1997), The effects of the water flow through the Canadian Archipelago in a global ice-ocean model, *Geophys. Res. Lett.*, *24*, 1507–1510, doi:10.1029/97GL01352.

Haak, H., J. Jungclaus, U. Mikolajewicz, and M. Latif (2003), Formation and propagation of Great Salinity Anomalies, *Geophys. Res. Lett.*, *30*(9), 1473, doi:10.1029/2003GL017065.

Haine, T. W. N., et al. (2015), Arctic freshwater export: Status, mechanisms, and prospects, *Global Planet. Change*, *125*, 13–35, doi:10.1016/j.gloplacha.2014.11.013.

Häkkinen, S. (1999), A simulation of thermohaline effects of a great salinity anomaly, *J. Clim.*, *12*(6), 1781–1795.

Hawkins, E., and R. Sutton (2009), Decadal predictability of the Atlantic Ocean in a coupled GCM: Forecast skill and optimal perturbations using linear inverse modeling, *J. Clim.*, *22*, 3960.

Heimbach, P., D. Menemenlis, M. Losch, J. M. Campin, and C. Hill (2010), On the formulation of sea-ice models. Part 2: Lessons from multi-year adjoint sea-ice export sensitivities through the Canadian Arctic Archipelago, *Ocean Modell.*, *33*(1), 145–158.

Held, I. M. (2005), The gap between simulation and understanding in climate modeling, *Bull. Am. Meteorol. Soc.*, *86*(11), 1609–1614.

Held, I. M., and B. J. Soden (2006), Robust responses of the hydrological cycle to global warming, *J. Clim.*, *19*(21), 5686–5699.

Hezel, P. J., X. Zhang, C. M. Bitz, B. P. Kelly, and F. Massonnet (2012), Projected decline in spring snow depth on Arctic sea ice caused by progressively later autumn open ocean freeze-up this century, *Geophys. Res. Lett.*, *39*, L17505, doi:10.1029/2012GL052794.

Hodson, D. L., S. P. Keeley, A. West, J. Ridley, E. Hawkins, and H. T. Hewitt (2013), Identifying uncertainties in Arctic climate change projections, *Clim. Dyn.*, *40*(11–12), 2849–2865.

Holland, M. M., and L. Landrum (2015), Factors affecting projected Arctic shortwave heating and albedo change in coupled climate models, *Philos. Trans R. Soc.*, doi:10.1098/rsta.2014.0162, in press.

Holland, M. M., C. M. Bitz, M. Eby, and A. J. Weaver (2001), The role of ice-ocean interactions in the variability of the North Atlantic thermohaline circulation, *J. Clim.*, *14*, 656–675.

Holland, M. M., J. Finnis, and M. C. Serreze (2006), Simulated Arctic Ocean freshwater budgets in the 20th and 21st centuries, *J. Clim.*, *19*, 6221–6242.

Holland, M. M., J. Finnis, A. P. Barrett, and M. C. Serreze (2007), Projected changes in Arctic Ocean freshwater budgets, *J. Geophys. Res.*, *112*, G04S55, doi:10.1029/2006JG000354.

Holland, M. M., M. C. Serreze, and J. Stroeve (2010), The sea ice mass budget of the Arctic and its future change as simulated by coupled climate models, *Clim. Dyn.*, *34*(2), 185–200, doi:10.1007/s00382-008-0493-4.

Holloway, G., and A. Proshutinsky (2007), Role of tides in Arctic ocean/ice climate, *J. Geophys. Res.*, *112*, C04S06, doi:10.1029/2006JC003643.

Holloway, G., et al. (2007), Water properties and circulation in Arctic Ocean models, *J. Geophys. Res.*, *112*, C04S03, doi:10.1029/2006JC003642.

1009 Hunke, E. C., D. Notz, A. K. Turner, and M. Vancoppenolle (2011), The multiphase physics of sea ice: A review for model developers, *Cryosphere*, *5*, 989, doi:10.5194/tc-5-989-2011.

Hunke, E. C., D. A. Herbert, and O. Lecomte (2013), Level-ice melt ponds in the Los Alamos sea ice model, CICE, *Ocean Modell.*, *71*, 26–42, doi:10.1016/j.ocemod.2012.11.008.

Hurrell, J. W., et al. (2013), The Community Earth System model: A framework for collaborative research, *Bull. Am. Meteorol. Soc.*, *94*(9), 1339–1360.

Hwang, Y. T., and D. M. Frierson (2010), Increasing atmospheric poleward energy transport with global warming, *Geophys. Res. Lett.*, *37*, L24807, doi:10.1029/2010GL045440.

Instanes, A., V. Kokorev, R. Janowicz, O. Bruland, K. Sand, and T. Prowse (2016), Changes to freshwater systems affecting Arctic infrastructure and natural resources, *J. Geophys. Res. Biogeosci.*, *121*, doi:10.1002/2015JG003125.

Intergovernmental Panel on Climate Change (IPCC) (2013), Climate change 2013—The physical science basis, in *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, pp. 1250, Cambridge Univ. Press, Cambridge, U. K., and New York.

Jahn, A., and M. M. Holland (2013), Implications of Arctic sea ice changes for North Atlantic deep convection and the meridional overturning circulation in CCSM4-CMIP5 simulations, *Geophys. Res. Lett.*, *40*, 1206–1211, doi:10.1002/grl.50183.

Jahn, A., B. Tremblay, L. A. Mysak, and R. Newton (2010a), Effect of the large-scale atmospheric circulation on the variability of the Arctic Ocean freshwater export, *Clim. Dyn.*, *34*, 201–222.

Jahn, A., L. B. Tremblay, R. Newton, M. M. Holland, L. A. Mysak, and I. G. Dmitrenko (2010b), A tracer study of the Arctic Ocean's liquid freshwater export variability, *J. Geophys. Res.*, *115*, C07015, doi:10.1029/2009JC005873.

Jahn, A., et al. (2012), Arctic Ocean freshwater: How robust are model simulations?, *J. Geophys. Res.*, *117*, C00D16, doi:10.1029/2012JC007907.

Johnson, M., et al. (2012), Evaluation of Arctic sea ice thickness simulated by Arctic Ocean Model Intercomparison Project models, *J. Geophys. Res.*, *117*, C00D13, doi:10.1029/2011JC007257.

Jorgenson, M. T., et al. (2013), Reorganization of vegetation, hydrology and soil carbon after permafrost degradation across heterogeneous boreal landscapes, *Environ. Res. Lett.*, *8*(3), 035017, doi:10.1088/1748-9326/8/3/035017.

Kalnay, E., et al. (1996), The NCEP/NCAR 40-Year Re-analysis Project, *Bull. Am. Meteorol. Soc.*, *77*, 437–471.

Karcher, M., R. Gerdes, F. Kauker, C. Koeberle, and I. Yashayaev (2005), Arctic Ocean change heralds North Atlantic freshening, *Geophys. Res. Lett.*, *32*, L21606, doi:10.1029/2005GL023861.

Karlsson, J., and G. Svensson (2013), Consequences of poor representation of Arctic sea-ice albedo and cloud-radiation interactions in the CMIP5 model ensemble, *Geophys. Res. Lett.*, *40*, 4374–4379, doi:10.1002/grl.50768.

Kattsov, V. M., J. E. Walsh, W. L. Chapman, V. A. Govorkova, T. V. Pavlova, and X. Zhang (2007), Simulation and projection of Arctic freshwater budget components by the IPCC AR4 global climate models, *J. Hydrometeorol.*, *8*(3), 571–589.

Kauker, F., T. Kaminski, M. Karcher, R. Giering, R. Gerdes, and M. Voßbeck (2009), Adjoint analysis of the 2007 all time Arctic sea-ice minimum, *Geophys. Res. Lett.*, *36*, L03707, doi:10.1029/2008GL036323.

Kay, J. E., et al. (2015), The Community Earth System Model (CESM) large ensemble project: A community resource for studying climate change in the presence of internal climate variability, *Bull. Am. Meteorol. Soc.*, *96*, 1333–1349, doi:10.1175/BAMS-D-13-00255.1.

Koeberle, C., and R. Gerdes (2003), Mechanisms determining the variability of Arctic sea ice conditions and export, *J. Clim.*, *16*(17), 2843–2858, doi:10.1175/1520-0442(2003)016<2843:MDTVOA>2.0.CO;2.

Koenigk, T., U. Mikolajewicz, H. Haak, and J. Jungclaus (2007), Arctic freshwater export in the 20th and 21st centuries, *J. Geophys. Res.*, *112*, G04S41, doi:10.1029/2006JG000274.

Koenigk, T., P. Berg, and R. Döscher (2015), Arctic climate change in an ensemble of regional CORDEX simulations, *Polar Res.*, *34*, doi:10.3402/polar.v34.24603.

Koven, C. D., W. J. Riley, and A. Stern (2013), Analysis of permafrost thermal dynamics and response to climate change in the CMIP5 Earth system models, *J. Clim.*, *26*(6), 1877–1900.

Koven, C. D., D. M. Lawrence, and W. J. Riley (2015), Permafrost-carbon feedback: Sensitivity to deep soil decomposability and nitrogen cycle, *Proc. Natl. Acad. Sci. U.S.A.*, doi:10.1073/pnas.1415123112.

Kwok, R. (2011), Observational assessment of Arctic Ocean sea ice motion, export, and thickness in CMIP3 climate simulations, *J. Geophys. Res.*, *116*, C00D05, doi:10.1029/2011JC007004.

Kwok, R., G. F. Cunningham, M. Wensnahan, I. Rigor, H. J. Zwally, and D. Yi (2009), Thinning and volume loss of the Arctic Ocean sea ice cover: 2003–2008, *J. Geophys. Res.*, *114*, C07005, doi:10.1029/2009JC005312.

Landerer, F. W., J. O. Dickey, and A. Guentner (2010), Terrestrial water budget of the Eurasian pan-Arctic from GRACE satellite measurements during 2003–2009, *J. Geophys. Res.*, *115*, D23115, doi:10.1029/2010JD014584.

Langehaug, H. R., F. Geyer, L. H. Smedsrud, and Y. Gao (2013), Arctic sea ice decline and ice export in the CMIP5 historical simulations, *Ocean Modell.*, *71*, 114–126.

Lawrence, D. M., and A. G. Slater (2008), Incorporating organic soil into a global climate model, *Clim. Dyn.*, *30*, 145–160, doi:10.1007/s00382-007-0278-1.

Lawrence, D. M., and A. G. Slater (2010), The contribution of snow condition trends to future ground climate, *Clim. Dyn.*, *34*, 969–981, doi:10.1007/s00382-009-0537-4.

Lawrence, D. M., A. G. Slater, V. E. Romanovsky, and D. J. Nicolsky (2008), The sensitivity of a model projection of near-surface permafrost degradation to soil column depth and inclusion of soil organic matter, *J. Geophys. Res.*, *113*, F02011, doi:10.1029/2007JF000883.

Lawrence, D. M., A. G. Slater, and S. C. Swenson (2012), Simulation of present-day and future permafrost and seasonally frozen ground conditions in CCSM4, *J. Clim. CCSM4 Spec. Collect.*, *25*, 2207–2225, doi:10.1175/JCLI-D-11-00334.1.

Lawrence, D. M., C. D. Koven, S. C. Swenson, W. J. Riley, and A. G. Slater (2015), Permafrost thaw and resulting soil moisture changes regulate projected high-latitude CO_2 and CH_4 emission, *Environ. Res. Lett.*, *10*, doi:10.1088/1748-9326/10/9/094011.

Laxon, S., N. Peacock, and D. Smith (2003), High interannual variability of sea ice thickness in the Arctic region, *Nature*, *425*, 947–950.

Lecomte, O., T. Fichefet, M. Vancoppenolle, F. Domine, F. Massonnet, P. Mathiot, S. Morin, and P. Y. Barriat (2013), On the formulation of snow thermal conductivity in large-scale sea ice models, *J. Adv. Model Earth Syst.*, *5*, 1–16, doi:10.1002/jame.20039.

Lee, H., S. C. Swenson, A. G. Slater, and D. M. Lawrence (2014), Effects of excess ground ice on projections of permafrost in a warming climate, *Environ. Res. Lett.*, *9*, doi:10.1088/1748-9326/9/12/124006.

Lemke, P., et al. (2007), Observations: Changes in snow, ice and frozen ground, in *Climate Change 2007: The Physical Science Basis*, edited by S. Solomon et al., pp. 337–383, Cambridge Univ. Press, New York.

Lettenmaier, D. P., and F. Su (2012), Chapter 9: Progress in hydrological modeling over high latitudes under Arctic Climate System Study (ACSYS), in *Arctic Climate Change: The ACSYS Decade and Beyond*, *Atmos. and Oceanogr. Sci. Library*, vol. 43, edited by P. Lemke and H.-W. Jacobi, pp. 357–380, Springer, Netherlands.

Lietaer, O., T. Fichefet, and V. Legat (2008), The effects of resolving the Canadian Arctic Archipelago in a finite element sea ice model, *Ocean Modell.*, *24*(3–4), 140–152.

Lindsay, R., M. Wensnahan, A. Schweiger, and J. Zhang (2014), Evaluation of seven different atmospheric reanalysis products in the Arctic, *J. Clim.*, *27*, 2588–2606, doi:10.1175/JCLI-D-13-00014.1.

Lindsay, R. W., and J. Zhang (2006), Arctic Ocean ice thickness: Modes of variability and the best locations from which to monitor them, *J. Phys. Oceanogr.*, *36*, 496–506, doi:10.1175/JPO2861.1.

Lipscomb, W. H., J. G. Fyke, M. Vizcaíno, W. J. Sacks, J. Wolfe, M. Vertenstein, A. Craig, E. Kluzek, and D. M. Lawrence (2013), Implementation and initial evaluation of the glimmer community ice sheet model in the Community Earth System model, *J. Clim.*, *26*(19), 7352–7371.

Lique, C., A. M. Treguier, M. Scheinert, and T. Penduff (2009), A model based study of ice and freshwater transport variability along both sides of Greenland, *Clim. Dyn.*, *33*(5), 685–705, doi:10.1007/s00382-008-0510-7.

Liston, G. E., and K. Elder (2006), A distributed snow-evolution modeling system (SnowModel), *J. Hydrometeorol.*, *7*, 1259–1276.

Long, M. C., K. Lindsay, and M. M. Holland (2015), Modeling photosynthesis in sea ice-covered waters, *J. Adv. Model. Earth Syst.*, *7*, 1189–1206, doi:10.1002/2015MS000436.

Long, Z., and W. Perrie (2013), Impacts of climate change on fresh water content and sea surface height in the Beaufort Sea, *Ocean Modell.*, *71*, 127–139.

Mahlstein, I., and R. Knutti (2010), Regional climate change patterns identified by cluster analysis, *Clim. Dyn.*, *35*(4), 587–600.

Martin, T., and R. Gerdes (2007), Sea ice drift variability in Arctic Ocean Model Intercomparison Project models and observations, *J. Geophys. Res.*, *112*, C04S10, doi:10.1029/2006JC003617.

Maslowski, W., J. Clement Kinney, M. Higgins, and A. Roberts (2012), The future of Arctic sea ice, *Annu. Rev. Earth Planet. Sci.*, *40*, 625–654, doi:10.1146/annurev-earth-042711-105345.

Massonnet, F., T. Fichefet, H. Goosse, C. M. Bitz, G. Philippon-Berthier, M. M. Holland, and P. Y. Barriat (2012), Constraining projections of summer Arctic sea ice, *Cryosphere*, *6*(6), 1383–1394.

Maykut, G. A. (1982), Large-scale heat exchange and ice production in the central Arctic, *J. Geophys. Res.*, *87*, 7971–7984, doi:10.1029/JC087iC10p07971.

McGuire, A. D., et al. (2012), An assessment of the carbon balance of Arctic tundra: Comparisons among observations, process models, and atmospheric inversions, *Biogeosciences*, *9*, 3185–3204, doi:10.5194/bg-9-3185-2012.

Medeiros, B., C. Deser, R. Tomas, and J. Kay (2011), Arctic inversion strength in climate models, *J. Clim.*, *24*, 4733–4740.

Meehl, G. A., C. Covey, B. McAvaney, M. Latif, and R. J. Stouffer (2005), Overview of the coupled model intercomparison project, *Bull. Am. Meteorol. Soc.*, *86*(1), 89–93.

Miller, J. R., and G. L. Russell (2000), Projected impact of climate change on the freshwater and salt budgets of the Arctic Ocean by a global climate model, *Geophys. Res. Lett.*, *27*, 1183–1186, doi:10.1029/1999GL007001.

Min, S.-K., X. B. Zhang, F. W. Zwiers, and T. Agnew (2008), Human influence on Arctic sea ice detectable from early 1990s onwards, *Geophys. Res. Lett.*, *35*, L21701, doi:10.1029/2008GL035725.

Mokhov, I. I., V. A. Semenov, and V. C. Khon (2003), Estimates of possible regional hydrologic regime changes in the 21st century based on global climate models, *Atmos. Oceanic Phys.*, *39*, 130–144.

Morison, J., R. Kwok, C. Peralta-Ferriz, M. Alkire, I. Rigor, R. Andersen, and M. Steele (2012), Changing Arctic Ocean freshwater pathways, *Nature*, *481*(7379), 66–70.

Morrison, H., and A. Gettelman (2008), A new two-moment bulk stratiform cloud microphysics scheme in the Community Atmosphere Model, Version 3 (CAM3). Part I: Description and Numerical Tests, *J. Clim.*, *21*, 3642–3659, doi:10.1175/2008JCLI2105.1.

Murphy, J. M., D. M. H. Sexton, D. N. Barnett, G. S. Jones, M. J. Webb, M. Collins, and D. A. Stainforth (2004), Quantification of modeling uncertainties in a large ensemble of climate change simulations, *Nature*, *430*, 768–772.

Nelson, F., and S. Outcalt (1987), A computational method for prediction and regionalization of permafrost, *Arct. Alp. Res.*, *19*, 279–288, doi:10.2307/1551363.

Newton, R., P. Schlosser, D. G. Martinson, and W. Maslowski (2008), Freshwater distribution in the Arctic Ocean: Simulation with a high-resolution model and model-data comparison, *J. Geophys. Res.*, *113*, C05024, doi:10.1029/2007JC004111.

Nguyen, A. T., D. Menemenlis, and R. Kwok (2009), Improved modeling of the Arctic halocline with a subgrid-scale brine rejection parameterization, *J. Geophys. Res.*, *114*, C11014, doi:10.1029/2008JC005121.

Nicolsky, D. J., V. E. Romanovsky, V. A. Alexeev, and D. M. Lawrence (2007), Improved modeling of permafrost dynamics in a GCM land-surface scheme, *Geophys. Res. Lett.*, *34*, L08501, doi:10.1029/2007GL029525.

Notz, D., and M. G. Worster (2009), Desalination processes of sea ice revisited, *J. Geophys. Res.*, *114*, C05006, doi:10.1029/2008JC004885.

Nugent, K. A., and H. D. Matthews (2012), Drivers of future northern latitude runoff change, *Atmos. Ocean*, *50*(2), 197–206.

Nurser, A. J. G., and S. Bacon (2014), The Rossby radius in the Arctic Ocean, *Ocean Sci.*, *10*, 967–975, doi:10.5194/os-10-967-2014.

Olsen, S. M., and T. Schmith (2007), North Atlantic-Arctic Mediterranean exchanges in an ensemble hindcast experiment, *J. Geophys. Res.*, *112*, C04010, doi:10.1029/2006JC003838.

Painter, S. L., J. D. Moulton, and C. J. Wilson (2013), Modeling challenges for predicting hydrologic response to degrading permafrost, *Hydrogeol. J.*, *21*(1), 221–224.

Polashenski, C., D. Perovich, and Z. Courville (2012), The mechanisms of sea ice melt pond formation and evolution, *J. Geophys. Res.*, *117*, C01001, doi:10.1029/2011JC007231.

Proshutinsky, A. Y., and M. A. Johnson (1997), Two circulation regimes of the wind-driven Arctic Ocean, *J. Geophys. Res.*, *102*, 12,493–12,514, doi:10.1029/97JC00738.

Proshutinsky, A., et al. (2001), Multinational effort studies differences among Arctic Ocean models, *Eos Trans. AGU*, *82*(51), 643–644, doi:10.1029/01EO00365.

Prowse, T., R. Shrestha, B. Bonsal, and Y. Dibike (2010), Changing spring air-temperature gradients along large northern rivers: Implications for severity of river-ice floods, *Geophys. Res. Lett.*, *37*, L19706, doi:10.1029/2010GL044878.

Prowse, T., A. Bring, J. Mård, and E. Carmack (2015a), Arctic Freshwater Synthesis: Introduction, *J. Geophys. Res. Biogeosci.*, *120*, doi:10.1002/2015JG003127.

Prowse, T., A. Bring, J. Mård, E. Carmack, M. Holland, A. Instanes, T. Vihma, and F. J. Wrona (2015b), Arctic Freshwater Synthesis: Summary of key emerging issues, *J. Geophys. Res. Biogeosci.*, *120*, 1887–1893, doi:10.1002/2015JG003128.

Räisänen, J. (2008), Warmer climate: Less or more snow?, *Clim. Dyn.*, *30*, 307–319, doi:10.1007/s00382-007-0289-y.

Rampal, P., J. Weiss, C. Dubois, and J. M. Campin (2011), IPCC climate models do not capture Arctic sea ice drift acceleration: Consequences in terms of projected sea ice thinning and decline, *J. Geophys. Res.*, *116*, C00D07, doi:10.1029/2011JC007110.

Rawlins, M. A., et al. (2010), Analysis of the Arctic system for freshwater cycle intensification: observations and expectations, *J. Clim.*, *23*(21), 5715–5737.

Rennermalm, A. K., E. F. Wood, A. J. Weaver, M. Eby, and S. J. Déry (2007), Relative sensitivity of the Atlantic Meridional Overturning Circulation to river discharge into Hudson Bay and the Arctic Ocean, *J. Geophys. Res.*, *112*, G04S48, doi:10.1029/2006JG000330.

Ridley, J. K., P. Huybrechts, J. M. Gregory, and J. A. Lowe (2005), Elimination of the Greenland Ice Sheet in a High CO_2 Climate, *J. Clim.*, *18*, 3409–3427, doi:10.1175/JCLI3482.1.

Rignot, E., I. Velicogna, M. R. Van den Broeke, A. Monaghanand, and J. T. M. Lenaerts (2011), Acceleration of the contribution of the Greenland and Antarctic ice sheets to sea level rise, *Geophys. Res. Lett.*, *38*, L05503, doi:10.1029/2011GL046583.

Riley, W. J., and C. Shen (2014), Characterizing coarse-resolution watershed soil moisture heterogeneity using fine-scale simulations, *Hydrol. Earth Syst. Sci.*, *18*(7), 2463–2483.

Riley, W. J., Z. M. Subin, D. M. Lawrence, S. C. Swenson, M. S. Torn, L. Meng, N. Mahowald, and P. Hess (2011), Barriers to predicting changes in global terrestrial methane fluxes: Analyses using a methane biogeochemistry model integrated in CESM, *Biogeosciences*, *8*, 1925–1953, doi:10.5194/bg-8-1925-2011.

Riseborough, D., N. Shiklomanov, B. Etzelmüller, S. Gruber, and S. Marchenko (2008), Recent advances in permafrost modeling, *Permafrost Periglacial Process.*, *19*(2), 137–156.

Roberts, A., A. Craig, W. Maslowski, R. Osinsk, A. Duvivie, M. Hughes, B. Nijssen, J. Cassano, and M. Brunke (2015), Simulating transient ice-ocean Ekman transport in the Regional Arctic System Model and Community Earth System Model, *Ann. Glaciol.*, *56*(69), 211–228, doi:10.3189/2015AoG69A760.

Rowland, J. C., et al. (2010), Arctic landscapes in transition: Responses to thawing permafrost, *Eos Trans. AGU*, *91*(26), 229–230, doi:10.1029/2010EO260001.

Rudels, B. (2011), Volume and freshwater transports through the Canadian Arctic Archipelago-Baffin Bay system, *J. Geophys. Res.*, *116*, C00D10, doi:10.1029/2011JC007019.

Rupp, D. E., P. W. Mote, N. L. Bindoff, P. A. Stott, and D. A. Robinson (2013), Detection and attribution of observed changes in Northern Hemisphere spring snow cover, *J. Clim.*, *26*, 6904–6914, doi:10.1175/JCLI-D-12-00563.1.

Schaefer, K., H. Lantuit, V. E. Romanovsky, E. A. Schuur, and R. Witt (2014), The impact of the permafrost carbon feedback on global climate, *Environ. Res. Lett.*, *9*(8), 085003, doi:10.1088/1748-9326/9/8/085003.

Schuur, E. A. G., et al. (2013), Expert assessment of vulnerability of permafrost carbon to climate change, *Clim. Change*, *119*(2), 359–374.

Schuur, E. A. G., et al. (2015), Climate change and the permafrost carbon feedback, *Nature*, *520*(7546), 171–179.

Screen, J. A., and I. Simmonds (2012), Declining summer snowfall in the Arctic: Causes, impacts and feedbacks, *Clim. Dyn.*, *38*, 2243–2256.

Serreze, M. C., and C. M. Hurst (2000), Representation of mean Arctic precipitation from NCEP-NCAR and ERA reanalyses, *J. Clim.*, *13*(1), 182–201.

Serreze, M. C., D. H. Bromwich, M. P. Clark, A. J. Ertringer, T. Zhang and R. Lammers (2002), Large-scale hydro-climatology of the terrestrial Arctic drainage system, *J. Geophys. Res.*, *107*(D2), 8160, doi:10.1029/2001JD000919.

Serreze, M. C., A. P. Barrett, A. G. Slater, R. A. Woodgate, K. Aagaard, R. B. Lammers, M. Steele, R. Moritz, M. Meredith, and C. M. Lee (2006), The large-scale freshwater cycle of the Arctic, *J. Geophys. Res.*, *111*, C11010, doi:10.1029/2005JC003424.

Serreze, M. C., A. P. Barrett, and J. Stroeve (2012), Recent changes in tropospheric water vapor over the Arctic as assessed from radiosondes and atmospheric reanalyses, *J. Geophys. Res.*, *117*, D10104, doi:10.1029/2011JD017421.

Shi, X., S. J. Déry, P. Y. Groisman, and D. P. Lettenmaier (2013), Relationships between recent hydroclimate trends, *J. Clim.*, *26*, 2048–2064, doi:10.1175/JCLI-D-12-00044.1.

Skific, N., J. A. Francis, and J. J. Cassano (2009), Attribution of projected changes in atmospheric moisture transport in the arctic: A self-organizing map perspective, *J. Clim.*, *22*, 4135–4153.

Slater, A. G., and D. M. Lawrence (2013), Diagnosing present and future permafrost from climate models, *J. Clim.*, *26*, 5608–5623.

Slater, A. G., T. J. Bohn, J. L. McCreight, M. C. Serreze, and D. P. Lettenmaier (2007), A multimodel simulation of pan-Arctic hydrology, *J. Geophys. Res.*, *112*, G04S45, doi:10.1029/2006JG000303.

St Jacques, J. M., and D. J. Sauchyn (2009), Increasing winter baseflow and mean annual streamflow from possible permafrost thawing in the Northwest Territories, Canada, *Geophys. Res. Lett.*, *36*, L01401, doi:10.1029/2008GL035822.

Stainforth, D. A., et al. (2005), Uncertainty in predictions of the climate response to rising levels of greenhouse gases, *Nature*, *433*, 403–406.

Steele, M., W. Ermold, S. Häkkinen, D. Holland, G. Holloway, M. Karcher, F. Kauker, W. Maslowski, N. Steiner, and J. Zhang (2001a), Adrift in the Beaufort Gyre: A model intercomparison, *Geophys. Res. Lett.*, *28*, 2935–2938, doi:10.1029/2001GL012845.

Steele, M., R. Morley, and W. Ermold (2001b), PHC: A global ocean hydrography with a high quality Arctic Ocean, *J. Clim.*, *14*, 2079–2087, doi:10.1175/1520-0442(2001)014<2079:PAGOHW>2.0.CO;2.

Steiner, N., et al. (2004), Comparing modeled stream function, heat and freshwater content in the Arctic Ocean, *Ocean Modell.*, *6*, 265–284.

Stewart, K. D., and T. W. N. Haine (2013), Wind-driven Arctic freshwater anomalies, *Geophys. Res. Lett.*, *40*, 6196–6201, doi:10.1002/2013GL058247.

Stroeve, J., A. Barrett, M. Serreze, and A. Schweiger (2014), Using records from submarine, aircraft and satellites to evaluate climate model simulations of Arctic sea ice thickness, *Cryosphere*, *8*, 1839–1854, doi:10.5194/tc-8-1839-2014.

Stroeve, J. C., V. Kattsov, A. Barrett, M. Serreze, T. Pavlova, M. Holland, and W. N. Meier (2012), Trends in Arctic sea ice extent from CMIP5, CMIP3 and observations, *Geophys. Res. Lett.*, *39*, L16502, doi:10.1029/2012GL052676.

Su, F., J. C. Adam, L. C. Bowling, and D. P. Lettenmaier (2005), Streamflow simulations of the terrestrial Arctic domain, *J. Geophys. Res.*, *110*, D08112, doi:10.1029/2004JD005518.

Swenson, S. C., D. M. Lawrence, and H. Lee (2012), Improved simulation of the terrestrial hydrological cycle in permafrost regions by the Community Land Model, *J. Adv. Model. Earth Syst.*, *4*, M08002, doi:10.1029/2012MS000165.

Swingedouw, D., C. B. Rodehacke, S. M. Olsen, M. Menary, Y. Gao, U. Mikolajewicz, and J. Mignot (2014), On the reduced sensitivity of the Atlantic overturning to Greenland ice sheet melting in projections: A multi-model assessment, *Clim. Dyn.*, *44*, 3261–3279.

Taylor, K. E., R. J. Stouffer, and G. A. Meehl (2012), An overview of CMIP5 and the experiment design, *Bull. Am. Meteorol. Soc.*, *93*(4), 485–498.

Tjernström, M., et al. (2005), Modelling the Arctic boundary layer: An evaluation of size ARCMIP regional-scale models using data from the SHEBA Project, *Boundary Layer Meteorol.*, *117*, 337–381.

Tsamados, M., D. L. Feltham, and A. V. Wilchinsky (2013), Impact of a new anisotropic rheology on simulations of Arctic sea ice, *J. Geophys. Res. Oceans*, *118*, 91–107, doi:10.1029/2012JC007990.

Tsubouchi, T., S. Bacon, A. C. Naveira Garabato, Y. Aksenov, S. W. Laxon, E. Fahrbach, A. Beszczynska-Möller, E. Hansen, C. M. Lee, and R. B. Ingvaldsen (2012), The Arctic Ocean in summer: A quasi-synoptic inverse estimate of boundary fluxes and water mass transformation, *J. Geophys. Res.*, *117*, C01024, doi:10.1029/2011JC007174.

Turner, A. K., and E. C. Hunke (2015), Impacts of a mushy-layer thermodynamic approach in global sea-ice simulations using the CICE sea-ice model, *J. Geophys. Res. Oceans*, *120*, 1253–1275, doi:10.1002/2014JC010358.

Turner, A. K., E. C. Hunke, and C. M. Bitz (2013), Two modes of sea-ice gravity drainage: A parameterization for large-scale modeling, *J. Geophys. Res. Atmos.*, *118*, 2279–2294, doi:10.1002/jgrc.20171.

Uttal, T., et al. (2002), Surface Heat Budget of the Arctic Ocean, *Bull. Am. Meteorol. Soc.*, *83*, 255–275.

Vage, K., R. S. Pickart, V. Thierry, G. Reverdin, C. M. Lee, B. Petrie, T. A. Agnew, A. Wong, and M. H. Ribergaard (2009), Surprising return of deep convection to the subpolar North Atlantic Ocean in winter 2007–2008, *Nat. Geosci.*, *2*, 67–72, doi:10.1038/NGEO382.

Vancoppenolle, M., L. Bopp, G. Madec, J. Dunne, T. Ilyina, P. R. Halloran, and N. Steiner (2013), Future Arctic Ocean primary productivity from CMIP5 simulations: Uncertain outcome, but consistent mechanisms, *Global Biogeochem. Cycles*, *27*, 605–619, doi:10.1002/gbc.20055.

Vavrus, S. J., M. M. Holland, A. Jahn, D. A. Bailey, and B. A. Blazey (2012), Twenty-first-century Arctic climate change in CCSM4, *J. Clim.*, *25*, 2696–2710.

Vihma, T., J. Screen, M. Tjernström, B. Newton, X. Zhang, V. Popova, C. Deser, M. Holland, and T. Prowse (2016), The atmospheric role in the Arctic water cycle: A review on processes, past and future changes, and their impacts, *J. Geophys. Res. Biogeosci.*, *121*, doi:10.1002/2015JG003132.

Vizcaíno, M., W. H. Lipscomb, W. J. Sacks, J. H. van Angelen, B. Wouters, and M. R. van den Broeke (2013), Greenland surface mass balance as simulated by the Community Earth System model. Part I: Model evaluation and 1850–2005 results, *J. Clim.*, *26*(20), 7793–7812.

Wadley, M. R., and G. R. Bigg (2002), Impact of flow through the Canadian Archipelago and Bering Strait on the North Atlantic and Arctic circulation: An ocean modelling study, *Q. J. R. Meteorol. Soc.*, *128*(585), 2187–2203.

Wania, R., I. Ross, and I. C. Prentice (2010), Implementation and evaluation of a new methane model within a dynamic global vegetation model: LPJ-WHyMe v1. 3.1, *Geosci. Model Dev.*, *3*(2), 565–584.

Wang, Q., et al. (2016), An assessment of the Arctic Ocean in a suite of interannual CORE-II simulations. Part II: Liquid freshwater, *Ocean Modelling*, *99*, 86–109.

Wettstein, J. J., and C. Deser (2014), Internal variability in projections of twenty-first-century Arctic sea ice loss: Role of the large-scale atmospheric circulation, *J. Clim.*, *27*(2), 527–550.

White, D., et al. (2007), The arctic freshwater system: Changes and impacts, *J. Geophys. Res.*, *112*, G04S54, doi:10.1029/2006JG000353.

Whitefield, J., P. Winsor, J. McClelland, and D. Menemenlis (2015), A new river discharge and river temperature climatology data set for the pan-Arctic region, *Ocean Modell.*, *88*, 1–15.

Woo, M. K., D. L. Kane, S. K. Carey, and D. Yang (2008), Progress in permafrost hydrology in the new millennium, *Permafrost Periglacial Process*, *19*(2), 237–254.

Woodgate, R. A., T. J. Weingartner, and R. Lindsay (2012), Observed increases in Bering Strait oceanic fluxes from the Pacific to the Arctic from 2001 to 2011 and their impacts on the Arctic Ocean water column, *Geophys. Res. Lett.*, *39*, L24603, doi:10.1029/2012GL054092.

Wrona, F. J., M. Johansson, J. M. Culp, A. Jenkins, J. Mård, I. H. Myers-Smith, T. D. Prowse, W. F. Vincent, and P. A. Wookey (2016), The atmospheric role in the Transitions in Arctic ecosystems: Ecological implications of a changing hydrological regime, *J. Geophys. Res. Biogeosci.*, *121*, doi:10.1002/2015JG003133.

Wu, P., R. Wood, and P. Stott (2005), Human influence on increasing Arctic river discharges, *Geophys. Res. Lett.*, *32*, L02703, doi:10.1029/2004GL021570.

Yang, D., D. Kane, Z. Zhang, D. Legates, and B. Goodison (2005), Bias corrections of long-term (1973–2004) daily precipitation data over the northern regions, *Geophys. Res. Lett.*, *32*, L19501, doi:10.1029/2005GL024057.

Yoshimori, M., A. J. Weaver, S. J. Marshall, and G. K. C. Clarke (2001), Glacial termination: Sensitivity to orbital and CO_2 forcing in a coupled climate system model, *Clim. Dyn.*, *17*, 571–588.

Zappa, G., L. C. Shaffrey, and K. I. Hodges (2013), The ability of CMIP5 models to simulate North Atlantic extratropical cyclones, *J. Clim.*, *26*, 5379–5396.

Zhang, J., and M. Steele (2007), Effect of vertical mixing on the Atlantic Water layer circulation in the Arctic Ocean, *J. Geophys. Res.*, *112*, C04S04, doi:10.1029/2006JC003732.

Zhang, X., M. Ikeda, and J. E. Walsh (2003), Arctic sea ice and freshwater changes driven by the atmospheric leading mode in a coupled sea ice-ocean model, *J. Clim.*, *16*(13), 2159–2177.

Zhang, X., J. He, J. Zhang, I. Polaykov, R. Gerdes, J. Inoue, and P. Wu (2013), Enhanced poleward moisture transport and amplified northern high-latitude wetting trend, *Nat. Clim. Change*, *3*, 47–51, doi:10.1038/NCLIMATE1631.