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The Future of Arctic Sea Ice

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Keywords

regional Arctic climate model, sea ice thickness and volume, Arctic Ocean, climate change, uncertainty of climate prediction, hierarchical Arctic climate modeling

Abstract

Arctic sea ice is a key indicator of the state of global climate because of both its sensitivity to warming and its role in amplifying climate change. Accelerated melting of the perennial sea ice cover has occurred since the late 1990s, which is important to the pan-Arctic region, through effects on atmospheric and oceanic circulations, the Greenland ice sheet, snow cover, permafrost, and vegetation. Such changes could have significant ramifications for global sea level, the ocean thermohaline circulation, native coastal communities, and commercial activities, as well as effects on the global surface energy and moisture budgets, atmospheric and oceanic circulations, and geosphere-biosphere feedbacks. However, a system-level understanding of critical Arctic processes and feedbacks is still lacking. To better understand the past and present states and estimate future trajectories of Arctic sea ice and climate, we argue that it is critical to advance hierarchical regional climate modeling and coordinate it with the design of an integrated Arctic observing system to constrain models.

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1. INTRODUCTION

The Arctic is a complex and integral part of the Earth system, influencing the global surface energy and moisture budgets, atmospheric and oceanic circulations, and geosphere-biosphere feedbacks. Its past-century records exhibit strong variability up to multidecadal timescales (e.g., Francis et al. 2009, Matthes et al. 2009), which likely results from the combined effects of natural variability and global warming (e.g., Serreze et al. 2009). However, model-based assessments of anthropogenic change in the Arctic are challenging and incomplete without the determination of its background natural variability (Vinnikov et al. 1999, Moritz & Bitz 2000, Holland et al. 2008). Prediction of decadal changes requires understanding, realistically simulating, and coupling the individual Arctic system components, which could be responding at different timescales to anthropogenic forcing.

Many studies confirm the importance of the Arctic in global climate evolution, including mechanisms that could cause abrupt climate change (e.g., Overpeck et al. 2005). Some key influences are related to the Arctic Oscillation (AO)/Northern Annular Mode (NAM) (Gong & Ho 2003, Buermann et al. 2005, Ju et al. 2005, Lim & Schubert 2011), the multiyear sea ice cover, and the ocean (e.g., Frankcombe & Dijkstra 2011). The sea ice cover is particularly important because it buffers air-sea heat fluxes (Washington & Meehl 1996, Rind et al. 1996) and through ice-albedo feedback (Perovich et al. 2002) strongly influences Earth's absorption of solar radiation. Global warming has been most visibly manifested in the Arctic through a declining perennial sea ice cover (e.g., Kwok et al. 2009), which has intensified during the late 1990s and the 2000s, resulting in a record minimum ice cover in 2007 (**Figures 1** and **2**). In contrast to previous decades, accelerated Arctic warming during the past decade has not been associated with a positive AO regime, implying the importance of oceanic forcing over longer timescales relative to atmospheric forcing acting alone. The absorption and accumulation of solar energy have increased in the Arctic Ocean as a result of these changes (Perovich et al. 2008, Jackson et al. 2011).

Indirectly, sea ice and freshwater export via the Fram Strait (Dickson et al. 1988) and the Canadian Archipelago (McGeehan & Maslowski 2011) can influence the strength of the meridional overturning circulation and multidecadal climate variability in the North Atlantic Ocean (e.g., Frankcombe & Dijkstra 2011). Studies of North Atlantic Deep Water properties (Dickson et al. 2002) suggest a multidecade freshening trend (Curry et al. 2003, Curry & Mauritzen 2005), which affects long-term global ocean heat and salt transport through linkages to the ocean thermohaline circulation. Growing evidence based on observations (Belkin et al. 1998, Dickson et al. 2002) and models (Holland et al. 2001, Maslowski et al. 2001) points to the Arctic Ocean as the main source of such changes. Similarly, a warming Arctic climate appears to affect the rate of melt of the Greenland ice sheet (Rignot & Kanagartnam 2006, van de Wal et al. 2008, Rennermalm et al. 2009), Northern Hemisphere permafrost (Smith et al. 2005), sea-level rise, and global climate change (IPCC 2007).

Arctic sea ice is also a sensitive indicator of the evolution of these changes as well as the state of Arctic climate as a whole (ACIA 2004). Satellite records of the Arctic sea ice cover show a decreasing trend in ice extent and concentration since the late 1970s (Stroeve & Maslowski 2007, Stroeve et al. 2011a). More importantly, sea ice thickness and volume have also been decreasing over the past few decades, possibly even faster than ice area (Stroeve & Maslowski 2007, Kwok & Rothrock 2009, Kwok et al. 2009). However, according to Kwok & Untersteiner (2011), the observed melting of Arctic sea ice over the past 50 years can be explained with $\sim$1 W m^{-2} of extra energy, the source of which is hard to attribute because of large uncertainties in observations and models of the Arctic energy balance. At the same time, reductions in the sea ice cover are believed to be the largest contributor toward Arctic amplification (i.e., higher than the global

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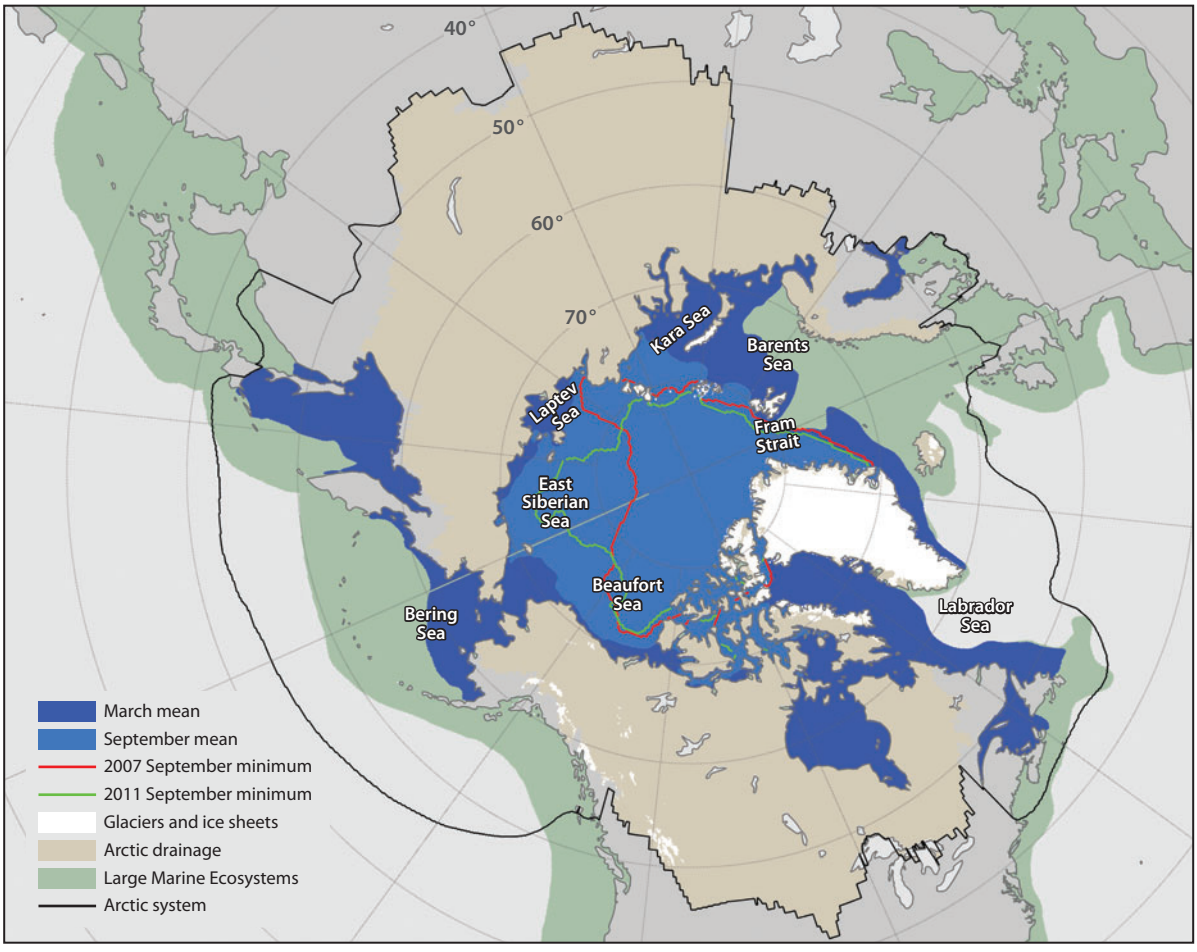

Figure 1

Mean sea ice extent for March and September (1979–2010) and record September minimum sea ice extents in years 2007 (lowest) and 2011 (second lowest) [data compiled from Comiso (1999) and Cavalieri et al. (2004) with updates from the National Snow and Ice Data Center (**http://www.nsidc.org**)]. The Arctic system domain as defined in Roberts et al. (2010) includes the sea ice zone, the land surface draining into the Arctic Ocean and associated terrestrial ecosystems, the area within the 10°C mean 1990–2000 surface temperature, and Large Marine Ecosystems, which include all areas covered by sea ice (as in Arctic Council 2009).

average temperature changes in the Arctic; Serreze et al. 2009, Screen & Simmonds 2010). Other important changes in the pan-Arctic region include the increase of permafrost active layer depth (Smith et al. 2005), upward trends in air temperature and precipitation (IPCC 2001), changes in precipitation patterns (Armstrong & Brodzik 2001), and warming of oceanic water masses advected from the North Atlantic and Pacific oceans into the Arctic Ocean (Shimada et al. 2006, Walczowski & Piechura 2006).

Such processes and feedbacks directly control regional Arctic climate variability and indirectly exert control on global climate variability. Their realistic representation in models is motivating development of computer models with very high spatiotemporal resolution and new parameterizations. This in turn is stimulating more robust model evaluation against long-term observations that represent scales that were until recently unresolved by even the highest-resolution Arctic

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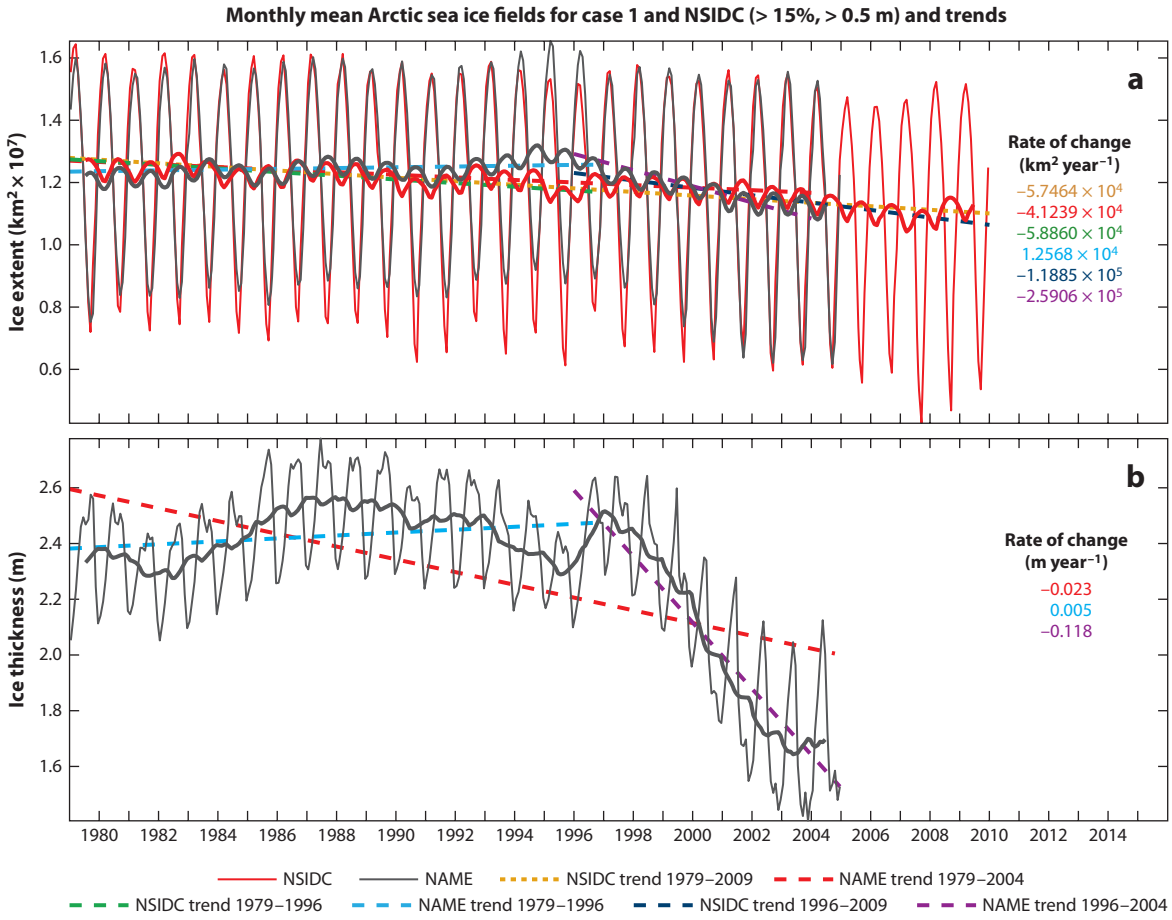

Figure 2

(*a*) Arctic sea ice extent from observations and model output. The thin red line is from NSIDC monthly mean data (1979–2011), and the thin dark gray line represents the NAME monthly mean model output (1979–2004). The thick red and dark gray lines represent 13-month running means from NSIDC data and NAME model output, respectively. (*b*) Sea ice thickness from the NAME model (Maslowski et al. 2004).

models. However, a system-level understanding of critical Arctic processes and feedbacks is still lacking. Fully coupled global climate models (GCMs) have large uncertainties[1] and limited skill in simulating and predicting the Arctic ice cover (e.g., Zhang & Walsh 2006, Bitz 2008) and related high-latitude climate sensitivity (Rind 2008). The majority of regional Arctic models use higher resolution compared with global models, but they do not account for important feedbacks among various system components. For example, they typically either simulate the atmospheric state using simplified lower boundary conditions for the sea ice and ocean (e.g., Wei et al. 2002, Tjernström et al. 2005, Rinke et al. 2006a,b) or predict sea ice–ocean variability using prescribed atmospheric forcing (e.g., Maslowski et al. 2004, Holloway et al. 2007, Kwok et al. 2008).

GCM: global climate model

[1]We use the term uncertainties to mean the variance in different model predictions, as opposed to the term skill, which is the variance in prediction errors of individual ensemble members (Hawkins & Sutton 2009) or single- and multimodel ensemble averages (Doblas-Reyes et al. 2005, Stroeve et al. 2007, Wang & Overland 2009).

Model limitations are hindering our ability to predict the future state of Arctic sea ice. A more realistic representation of time-dependent conditions of the Arctic sea ice cover and their effect on air-sea interactions is necessary in regional models, and it requires coupling the respective model components.

Disentangling the relative importance of these and other sources of uncertainty in modeling of Arctic sea ice and climate presents a major challenge. Part of the solution rests in improving the representation of processes within both regional climate models and GCMs through increased model resolution and improved parameterizations. Another part of the solution lies in increasing the number of Arctic processes included in models to explore their nonlinear influences on climate evolution, as well as expanding the biogeochemistry and ecological capabilities. However, this will also increase the complexity of global Earth system models (GESMs), which will most likely increase uncertainty in climate projections (Hawkins & Sutton 2009). For that reason, there is growing interest in the combined use of GESMs with regional modeling tools and expertise to help understand uncertainty and improve the quality of probabilistic projections (Giorgi 2005), which we refer to as hierarchical modeling.

GESM: global Earth system model

CMIP5: Coupled Model Intercomparison Project 5

ASM: Arctic system model

This review focuses on the fate of the Arctic sea ice and the need for a hierarchical modeling approach to advance simulations of future Arctic sea ice. Section 2 gives an overview of the declining trend of the Arctic sea ice cover for the past few decades. Section 3 discusses the role of the atmospheric forcing of sea ice as well as climate model representations of observed states of atmospheric circulation in selected global Coupled Model Intercomparison Project 5 (CMIP5) models. Section 4 summarizes past sea ice variability and future predictions based on results of selected CMIP3 and CMIP5 models. Section 5 details critical model limitations and biases in simulating sea ice conditions, variability, and fluxes. Throughout, we use a regional model as a working example for comparison with global projections and provide a rationale for the continued and parallel development of regional Arctic system models (ASMs) with GESMs to understand and improve skill and reduce uncertainty in Arctic sea ice predictions.

2. STATE AND PROJECTIONS OF ARCTIC SEA ICE

Relative to trends over the last few decades, warming in the Arctic Ocean has accelerated during the past several years, as observed by satellites and in situ measurements. The main manifestation of such a warming trend has been the melting of the Arctic perennial ice pack and the dramatic reduction of summer sea ice cover (Stroeve et al. 2008). Satellite records of the Arctic summer minimum sea ice extent show a decreasing trend of −6.5% per decade during 1979–2001. This trend accelerates to −8.6% per decade when the record is extended through 2005 and continues accelerating with –10.2% per decade in September 2007 down to −12.0% per decade through September 2011 (Stroeve & Maslowski 2007, Stroeve et al. 2011a). When compared to the long-term mean of 1979–2000, the Arctic sea ice extent in September of 2007 was almost 40% below average, and it has remained well below average from September 2005 through 2011 (**Figure 1**).

However, this satellite-derived measure of warming in the Arctic provides only aerial diagnostics (i.e., two dimensional) in contrast to the measure of total Arctic sea ice volume (i.e., three dimensional), which would require knowledge of sea ice–thickness distribution in space and time. When comparing relative changes in September ice extent [both observed and modeled (**Figure 2*a***)] and modeled ice thickness (**Figures 2*b*** and **3**) between 1979 and 2002, we see that the relative change in ice thickness (~44%) is more than twice the change of ice extent/area decrease (~16%) over that period. Trend estimates in sea ice extent and thickness for different time periods are provided (**Figure 2**) for comparison with similar approaches by Comiso et al. (2008) and Stroeve et al. (2011b), as well as to emphasize the large uncertainty of such estimates

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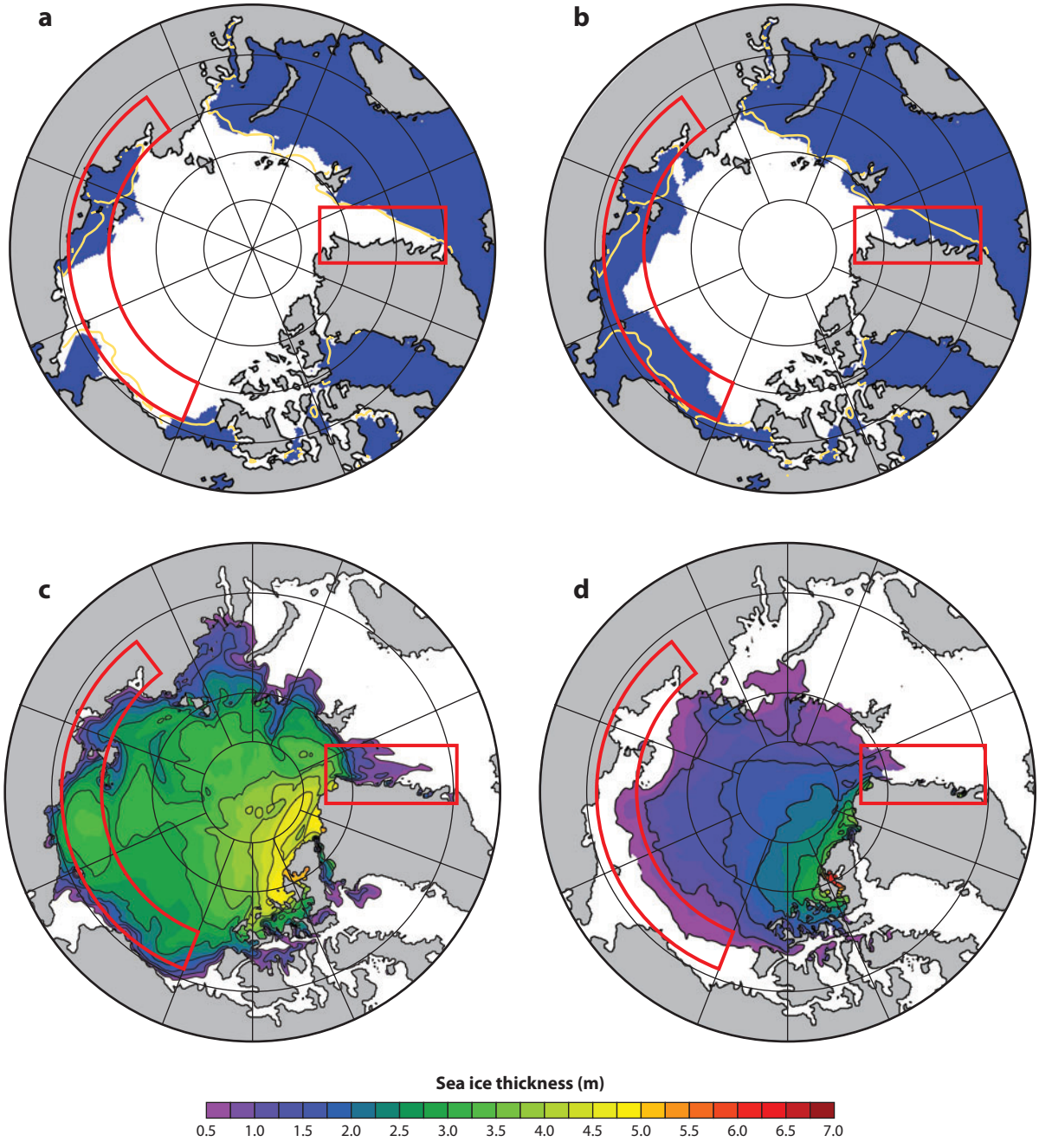

Figure 3

Comparison of (*a*,*b*) observed (NSIDC) September ice extent with (*c*,*d*) NAME modeled ice extent and thickness during (*a*,*c*) 1988 and (*b*,*d*) 2002.

(depending on the time period and parameter used), and to indicate that this relationship is likely to change in the future. As ice thins, the seasonal reduction of sea ice extent/area increases because larger regions covered by thinner sea ice become subject to summer melt. Both surface ice melt due to warmer air above and under-ice melt due to the warmer upper ocean can contribute to changes in ice thickness. In addition, the mechanical redistribution of ice thickness within the basin and variations of sea ice export out through the Fram Strait and also into the Barents Sea exert regional or basin-wide changes in the Arctic sea ice–volume budget (Kwok et al. 2005, 2008; Kwok 2009).

NAME: Naval Postgraduate School Arctic Modeling Effort

SLP: sea-level pressure

Figure 2*a* provides estimates obtained using the Naval Postgraduate School Arctic Modeling Effort (NAME) regional ice-ocean model (Maslowski et al. 2004). This is a regional hindcast model driven by daily reanalyzed and operational surface atmospheric data from the European Centre for Medium-Range Weather Forecasts (ECMWF; Gibson et al. 1997) and by the surface Polar Science Center Hydrographic Climatology (Steele et al. 2001). We use it as a working example of a regional model through much of this review. Because NAME is regionally constrained by atmospheric forcing and boundary conditions, it allows synthesis and provides an estimate of changes in sea ice thickness and volume useful for understanding the skill and uncertainty[1] of climate projections from more complex models with coupled atmospheric and terrestrial surface components (Arctic and global Earth system models).

There are still insufficient observations of ice thickness to quantify the basin-wide and long-term rate of ice-volume change over the past several decades (Kwok et al. 2009). However, these data—limited submarine upward-looking sonar observations of ice draft [approximately 89% of the thickness (Rothrock et al. 2008)] and more recent satellite estimates of ice thickness and volume [based on measurements of ice freeboard (Laxon et al. 2003, Kwok & Rothrock 2009, Kwok et al. 2009)]—are useful for evaluating the performance of models such as NAME. For example, **Figure 4** shows that the NAME model represents the observed decrease in sea ice thickness between 1988 and 2004 and further exemplifies the dramatic loss of ice thickness before and after the late 1990s. Similar comparisons are routinely conducted for a host of variables and models used for the Arctic, both regional and global, and illustrate the importance of observations to constrain models and to optimize the reconstruction of basin-wide and long-term sea ice thickness and volume.

3. ATMOSPHERIC FORCING OF SEA ICE

The Arctic atmosphere plays a central role in the evolution of sea ice movement, growth, and melting. Recent studies have shown that lower atmospheric winds are responsible for half the variance in sea ice extent and one-third of the downward trend in sea ice extent over the past several decades (~30%) (Ogi et al. 2010). At the local level, anomalous sea ice motion in the Fram Strait is primarily driven by sea-level pressure (SLP) anomalies (Tsukernik et al. 2010), and specific changes in circulation are largely believed to be responsible for the record low in sea ice cover experienced in 2007 (Comiso et al. 2008). Sea ice loss can be further enhanced by the radiative forcing of clouds. Increased cloudiness can trap outgoing longwave radiation, reradiating it back to the surface (Vavrus et al. 2011), but decreased cloudiness can result in increased shortwave radiation at the surface (Kay et al. 2008).

Compared with patterns seen in the twentieth century, Arctic atmospheric patterns have been notably different in the twenty-first century, and this change in atmospheric circulation has significantly contributed to sea ice decline (Overland et al. 2008, Overland & Wang 2010). This shift toward a positive Arctic Dipole (AD) pattern results in meridional wind anomalies, as opposed to primarily zonal wind anomalies seen in AO patterns in the twentieth century.

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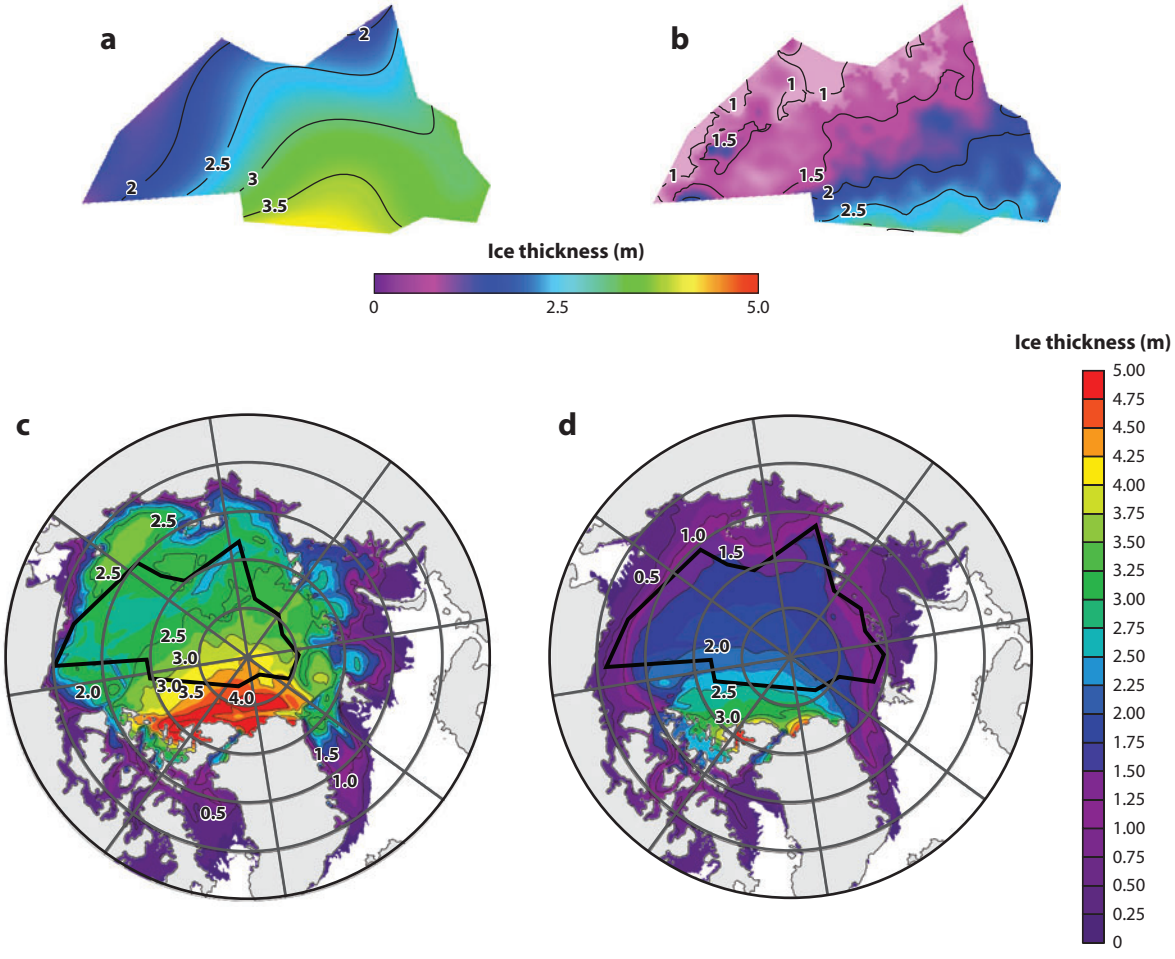

Figure 4

Comparison of the change in Arctic sea ice thickness before and after 2000 from observations and the NAME model: (*a*) October through December 1988 from submarine observations, (*b*) October through November 2003–2008 from ICESat observations (as in Kwok & Rothrock 2009), and (*c*,*d*) NAME model data from (*c*) October through November 1988 and (*d*) October through November 2004.

The summer of 2007 is a prime example of the influence of this type of forcing. In 2007, the ice cover reached the lowest area on record in large part because of atmospheric forcing (Comiso et al. 2008, Zhang et al. 2008). In August 2007, a persistent and strong AD pattern advected the sea ice away from the western Arctic (Wang et al. 2009) toward the central Arctic, with the specific strength and location of the SLP pattern favoring extremely rapid ice retreat (Ogi et al. 2008).

In addition to physically advecting sea ice in 2007, the synoptic patterns also contributed to changes in the surface energy budget, further enhancing sea ice loss. The strong anticyclonic pattern centered over the Beaufort Sea and North American Arctic Basin over the 2007 summer resulted in reduced cloudiness and significantly enhanced downwelling shortwave radiation (Kay et al. 2008). This increase in downwelling radiation ultimately resulted in a 500% increase in solar heat input into the ocean through an accelerated ice-albedo feedback (Perovich et al. 2008). In

addition, the meridonial flow of warm and humid air into the Arctic from the AD pattern yielded an increase in downward longwave radiation and turbulent fluxes, enhancing the melt (Graversen et al. 2011).

CCSM4: Community Climate System Model version 4

The AO was strongly negative in the winter of 2009–2010, a pattern that typically favors the growth of multiyear ice (Proshutinsky & Johnson 1997). This pattern should have favored minimal sea ice loss in the summer of 2010, yet sea ice extent in the summer was the third lowest on record. This apparent dichotomy results from shifts in the atmospheric forcing of ice transport associated with the 2009–2010 AO pattern (Stroeve et al. 2011a) and an ongoing decrease in the fraction of multiyear ice (Maslanik et al. 2011).

In addition to the atmosphere affecting the sea ice extent and volume, changes in the sea ice and ocean also feed back to the atmosphere. Studies in recent years have shown that declining sea ice will result in an increase in both the frequency and the intensity of cyclonic and anticyclonic synoptic-scale systems (Higgins & Cassano 2009).

Given the importance of atmospheric circulation in forcing sea ice growth, melt, and transport, how well do current state-of-the-art GCMs simulate the Arctic circulation? Although these models are useful for many aspects of climate research, based on the results presented below, we believe that further improvements are possible and needed to correctly represent the atmospheric circulation in the Arctic. Not only must large-scale circulation patterns such as AO and AD be well represented in models, but smaller, regional patterns are important as well. These smaller patterns are often the primary drivers in determining ice transport, and subtle shifts in these patterns have significant impacts on it (Maslanik et al. 2007, Kwok 2009).

In many GCMs, there are large biases in atmospheric circulation, and it seems probable that these biases will have major impacts on the ability of these models to accurately predict changes in sea ice. For example, in the CMIP3 era of GCMs, nearly all the models produced a large, positive SLP bias (average of +9 mb) centered over the Barents Sea (Chapman & Walsh 2007). This error causes incorrect sea ice advection along the coast of the Kara and Barents Seas and into the North Atlantic. It is not surprising that the Barents Sea in particular shows the largest spread of sea ice distribution and thickness in the Arctic among the CMIP3 models (Holland et al. 2010).

Part of the CMIP5 era of GCMs, the recently released Community Climate System Model version 4 (CCSM4) (Gent et al. 2011) shows major circulation biases as compared with ECMWF 40-year reanalysis data (ERA-40; **Figure 5**). In CCSM's projection of winter atmospheric circulation (**Figure 5**, top left), the Beaufort High is poorly simulated, and the North Atlantic storm track is both too intense and incorrectly shifted to the northeast. These errors result in a significant low SLP bias across the Arctic of >12 mb (de Boer et al. 2011). This underprediction of the Beaufort High causes a poor representation of sea ice motion in the Beaufort Gyre (Jahn et al. 2011). CCSM4 is not alone in Arctic circulation biases; many models participating in CMIP5 show significant circulation biases (both positive and negative) throughout the year. **Figure 6** illustrates winter Arctic SLP biases for single ensemble members of several of the CMIP5 models. These biases are quite varied, ranging from −12 mb to +8 mb, and will significantly impact sea ice prediction through incorrectly applied surface wind stresses and incorrect temperature advection. Other seasons (not shown in the figure) show substantial circulation biases as well.

4. MODELING OF FUTURE ARCTIC SEA ICE CHANGE

Over the past decade, various studies have attempted to estimate the future trajectory of Arctic climate and have proposed a wide range of projections of seasonal Arctic sea ice cover. We

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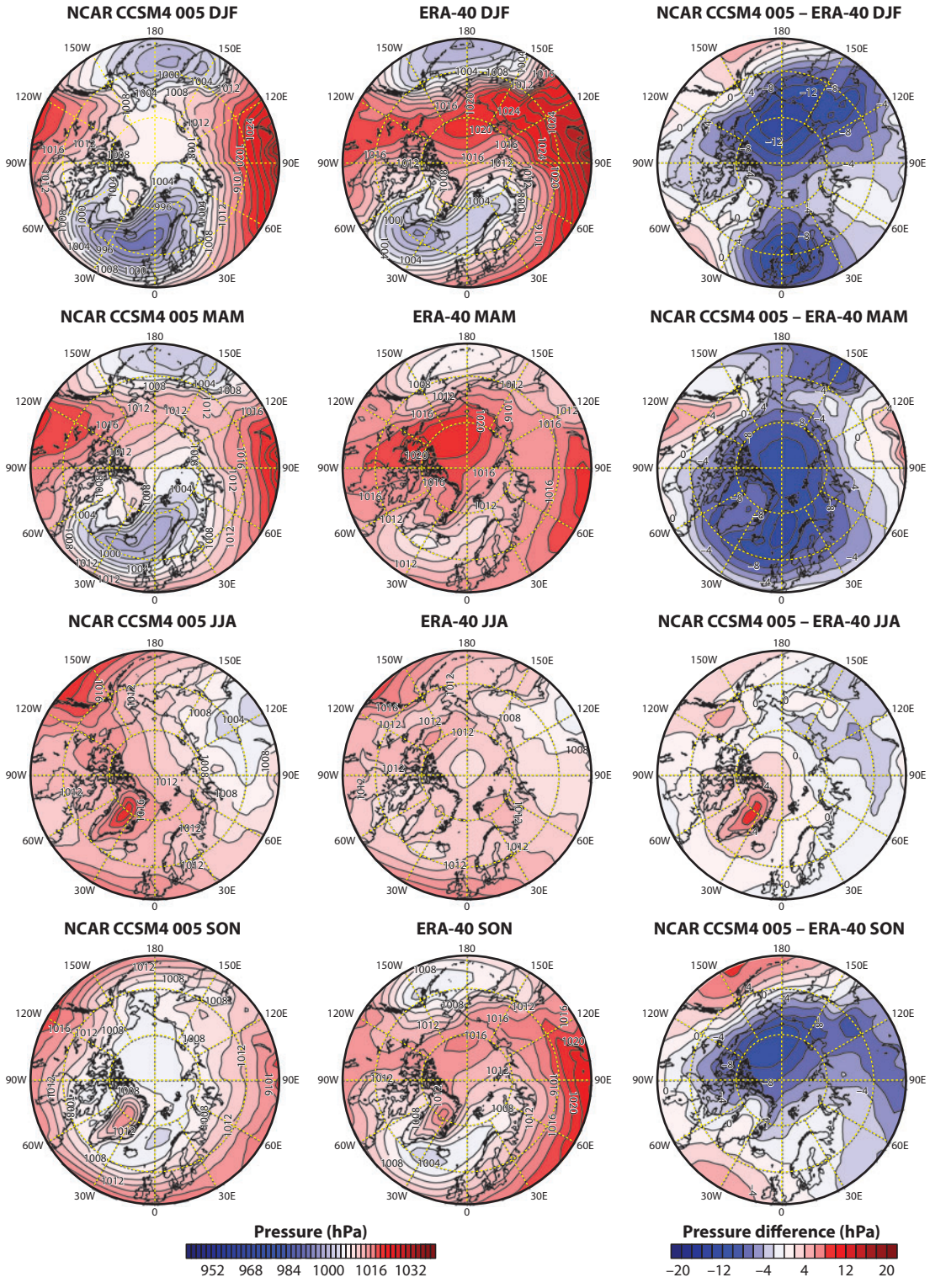

summarize most of these projections below to emphasize that more work is needed to minimize confusion, identify uncertainty, and advance the prediction of Arctic sea ice change.

GCMs used in the Arctic Climate Impact Assessment studies on average predict more than a 50% reduction of summer sea ice cover in the Arctic Ocean by the end of this century (ACIA 2004). GCMs participating in the World Climate Research Programme (WCRP) CMIP2 predict a little over 10% decrease of sea ice concentration in response to doubling of CO_2 (Hu et al. 2004). Models participating in the Intergovernmental Panel for Climate Change Fourth Assessment Report (IPCC AR4) and in CMIP3 suggest the reduction of sea ice cover to an almost ice-free Arctic Ocean in summer by the end of this century (Johannessen et al. 2004, Zhang & Walsh 2006), and by 2040 in the most extreme predictions (e.g., Holland et al. 2006). Unfortunately, the majority of GCMs, including those participating in the IPCC AR4, have not been able to adequately reproduce observed multidecadal sea ice variability and trends in the pan-Arctic region (Stroeve et al. 2007). The ensemble multimodel mean trend in September Arctic sea ice extent from 1953 to 2006 is too conservative; it is approximately 30 years behind the observed trend. Using a subset of better-performing IPCC AR4 GCMs to provide improved regional projections of Arctic sea ice, Overland & Wang (2007) projected over 40% loss of sea ice area over the marginal seas of the Arctic Ocean by 2050 in summer. In a following study, using extended observations of the Arctic sea ice minimum through 2008 as an initial point for interpolating results from six IPCC AR4 models, Wang & Overland (2009) projected a nearly sea ice–free Arctic Ocean in September by 2037. Another independent, yet nonanalytical, estimate by Stroeve et al. (2008) brings this projection even closer.

Model representation of sea ice thickness presents additional challenges as it involves not only thermodynamic interaction with the ocean below, but also the dynamic and thermodynamic effects from the atmosphere above. Similarly to results on the Arctic sea ice thickness in **Figure 2*b***, Gerdes & Koberle (2007) found no trend in the regional model hindcast for the period from 1948 through the 1990s and identified considerable deficiencies in the CMIP3 GCMs related to the spatial distribution of ice thickness, ice rheology, and air-sea-ice interactions. In addition to large sea ice model-data differences, Kwok (2011) also found significant biases in large-scale atmospheric circulation patterns critical to determining spatial patterns in sea ice conditions, which implies considerable uncertainties in the projected rates of sea ice decline.

More recently, results from several models participating in the CMIP5 program have become available. The initial analyses of sea ice–model output from the latest version of the National Center for Atmospheric Research (NCAR) CCSM4 (Kay et al. 2011, Vavrus et al. 2011) yield similar, yet somewhat more conservative results compared with CMIP3 predictions of Arctic sea ice decline. We have analyzed results from eight of the CMIP5 models that have become available. Results for the mean September ice-thickness distributions during the time period of 2000–2004 are shown in **Figure 7**. Four of the models have quite unrealistic distributions of sea ice thickness for this period (BCC, CanESM2, GISS-E2-H, and GISS-E2-R). The other four CMIP5 models are more accurate, but some problems remain. For example, the NorESM1-M and IPSL simulations overestimate both sea ice extent and thickness distribution. The NCAR and HadGEM2 simulations show a reasonable thickness distribution; however, the extent is too

Figure 5

Seasonal mean sea-level pressure averaged from 1979 to 2002 for a CCSM ensemble member (*left column*), ERA-40 (European Centre for Medium-Range Weather Forecasts 40-year reanalysis data) (*middle column*), and the difference between the two (*right column*). Figure adapted from de Boer et al. (2011).

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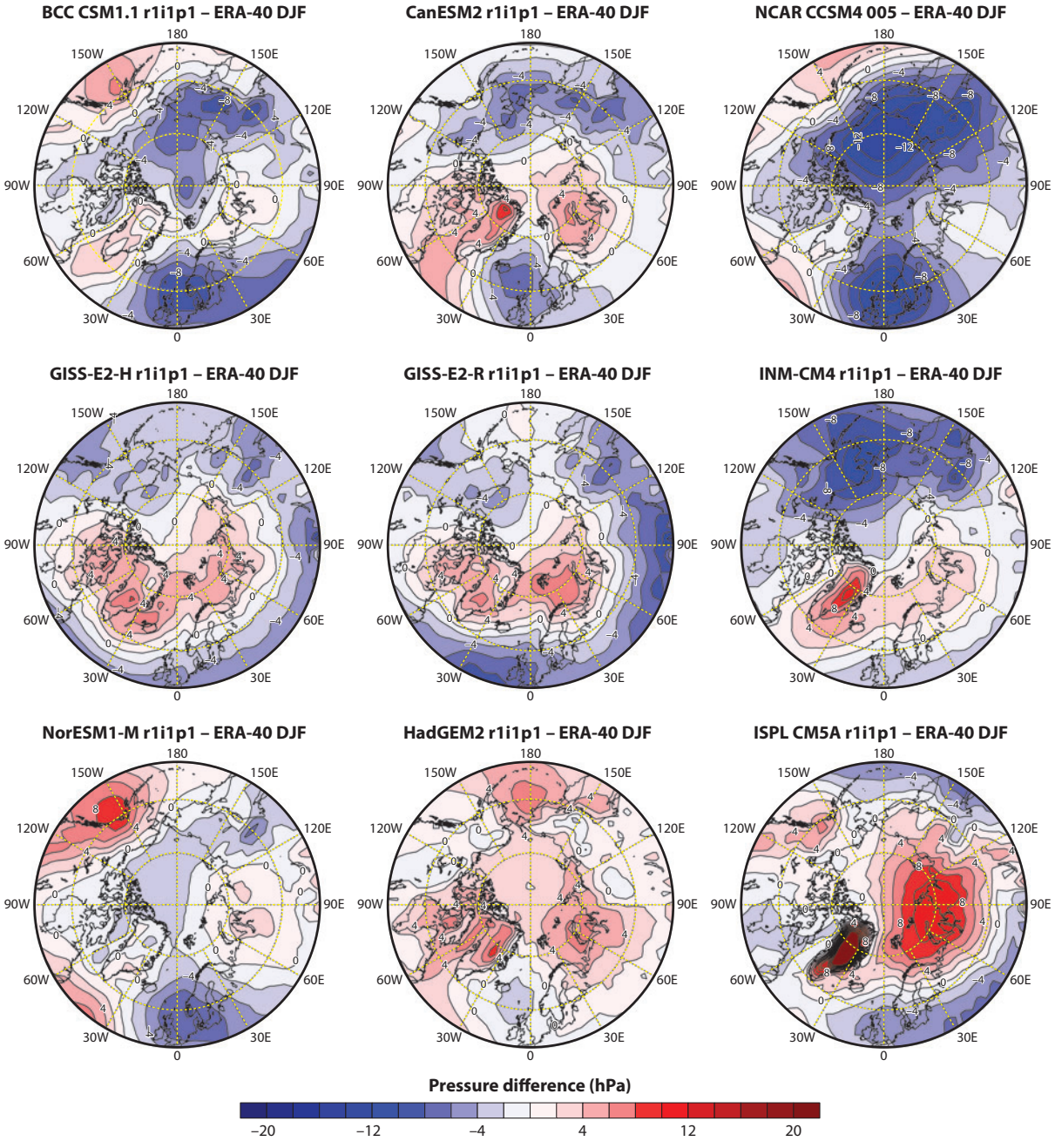

Figure 6

Differences in winter mean sea-level pressure averaged from 1979 to 2002 for nine CMIP5 global climate models versus ERA-40 (European Centre for Medium-Range Weather Forecasts 40-year reanalysis data).

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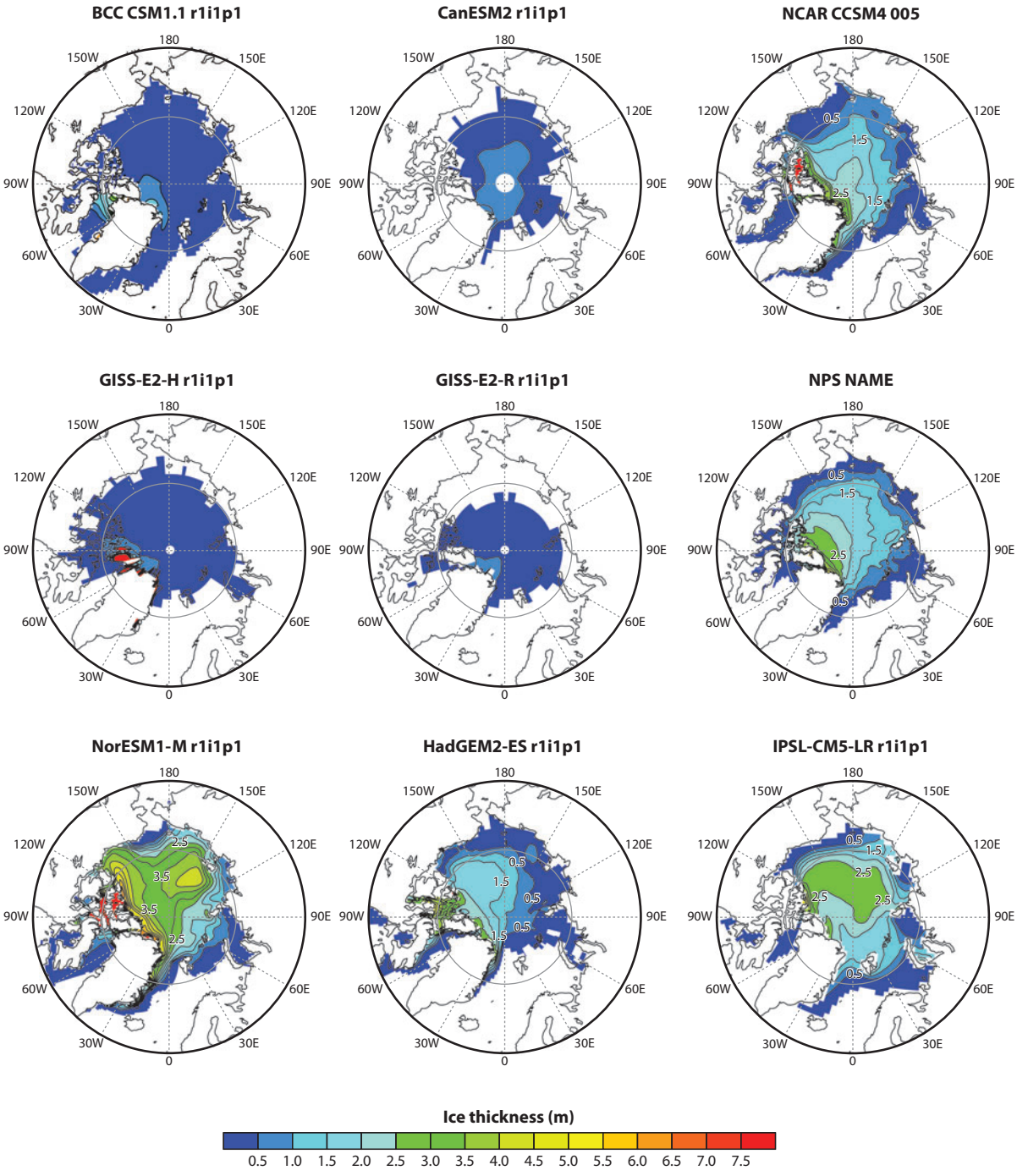

Figure 7

September mean sea ice thickness (m) averaged over 2000–2004 from CMIP5 and NAME models.

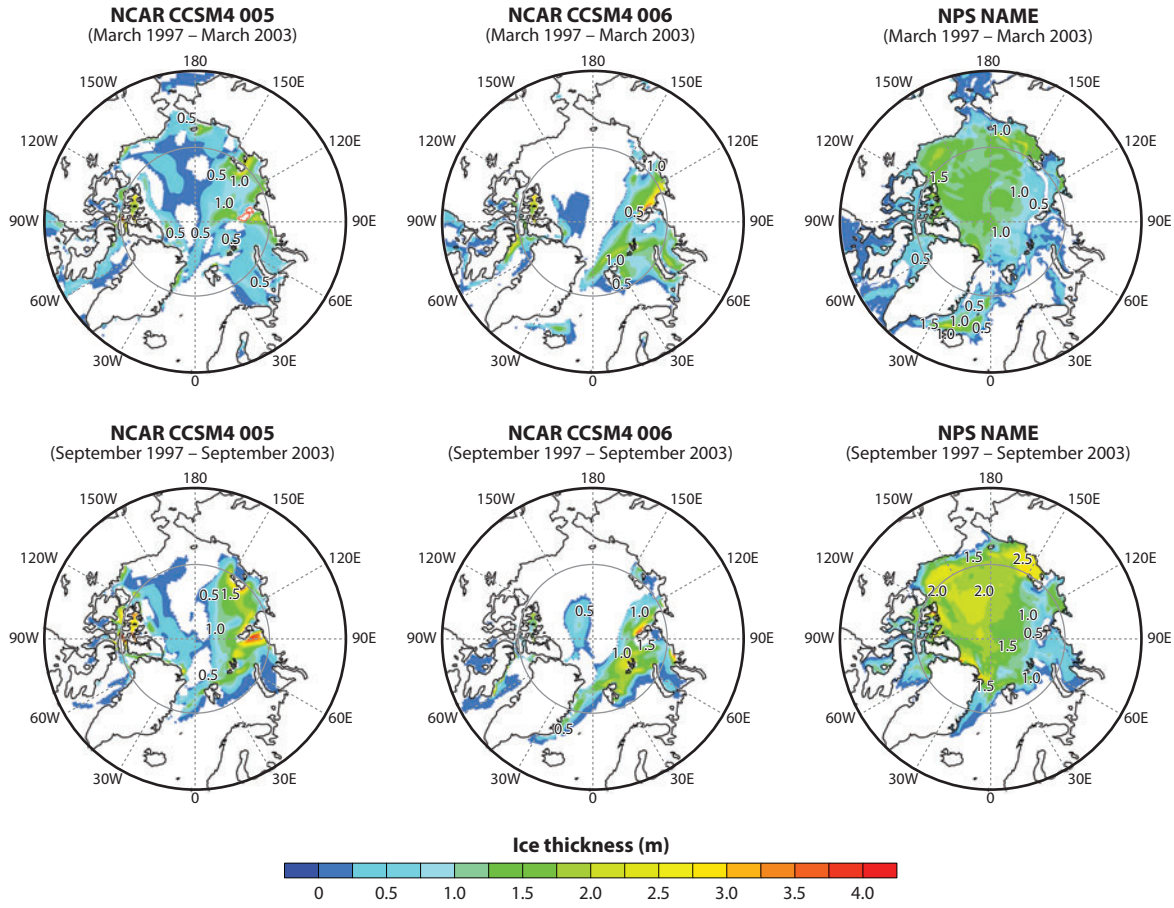

Figure 8

Sea ice–thickness (m) difference between 1997 and 2003 during (*top row*) March and (*lower row*) September from (*left column*) CCSM4 b40.20th.track1.1deg.005, (*center column*) CCSM4 b40.20th.track1.1deg.006, and (*right column*) the NAME model.

great relative to observations and the observationally constrained NAME model, which shows a realistic thickness distribution, with a slightly overestimated extent.

Although observations are limited (e.g., Kwok et al. 2009, Maslanik et al. 2011), there is a consensus that the decrease of the Arctic sea ice thickness and the extent of multiyear sea ice have been extensive and dramatic. **Figure 8** shows the difference in ice thickness between 1997 and 2003 for two ensemble runs from CCSM4, one of the best CMIP5 models at simulating sea ice extent. Neither of the ensemble runs from CCSM4 shows the overall thinning of sea ice throughout the Arctic as the NAME model does. A clear decline in thickness of up to 1.5 m is present during March and up to 2 m during September in the NAME model. CCSM4 results show only some spotty, local thinning in the Canadian Arctic Archipelago and the eastern Arctic.

The inability of climate models to adequately reproduce the recent states and trends of Arctic sea ice diminishes confidence in their accuracy for making future climate predictions. Another issue is that sea ice extent and area are parameters that only partially account for the loss of sea ice volume. An unrealistic sea ice–thickness distribution will affect the modeled ice extent and area as well as volume, which in turn may delay (or accelerate) predicted changes in seasonal sea ice

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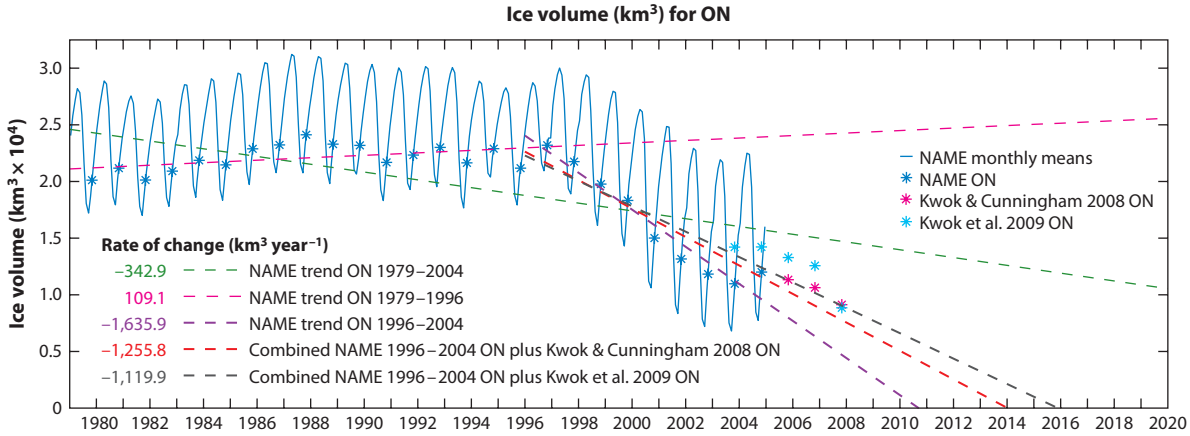

Figure 9

Arctic sea ice–volume estimates from observations and from the NAME model. For the observations, the October–November (ON) means are illustrated for 2003–2007, taken from Kwok & Cunningham (2008) (*magenta stars*) and Kwok et al. (2009) (*light blue stars*). For the NAME model, the time series of monthly means for 1979–2004 (*solid blue line*) and the ON mean (*blue stars*) are shown. The dashed green line is the model ON trend for 1979–2004. The dashed magenta line is the model ON trend for 1979–1996, and the dashed purple line is the model ON trend for 1996–2004. The red and dark gray dashed lines show the calculated linear trend for 1996–2007 [combined NAME/ON 1996–2004 plus Kwok & Cunningham (2008) and combined NAME/ON 1996–2004 plus Kwok et al. (2009), respectively]. The numbers labeled rate of change are sea ice–volume trends per year based on different results shown in the symbol key.

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cover in the Arctic Ocean. This fact emphasizes the need for detailed analyses of changes in sea ice thickness and volume to determine the actual rate of melt of Arctic sea ice.

An attempt to do that is presented in **Figure 9**, which shows a time series of monthly mean Arctic sea ice volumes from the NAME model and recent satellite estimates. According to model results, sea ice volume has changed little during the 1980s through the mid-1990s (i.e., no noteworthy trend is present during this time period), in contrast to the time period after 1995. This is qualitatively consistent with trend estimates for the ice extent [**Figure 2*a*** (Stroeve et al. 2011b)] and thickness (**Figures 2*b*** and **8**) and demonstrates a strengthening of the trends in all three sea ice parameters on the basis of a statistically significant difference in linear regression slopes computed for the two time periods. The modeled evolution of Arctic sea ice volume appears to be more strongly correlated with changes in ice thickness than with ice extent as it shows a similar negative trend beginning around the mid-1990s. When considering this part of the sea ice–volume time series, one can estimate a negative trend of $-1{,}120$ km^3 year^{-1} with a standard deviation of $\pm 2{,}353$ km^3 year^{-1} from combined model and most recent observational estimates for October–November 1996–2007. Given the estimated trend and the volume estimate for October–November of 2007 at less than 9,000 km^3 (Kwok et al. 2009), one can project that at this rate it would take only 9 more years or until 2016 $\pm$ 3 years to reach a nearly ice-free Arctic Ocean in summer. Regardless of high uncertainty associated with such an estimate, it does provide a lower bound of the time range for projections of seasonal sea ice cover. (We do note that other published estimates also have large or indeterminate uncertainties.) At the same time, observational proxies of ice thickness (Maslanik et al. 2011) and independent model estimates (Polar Science Center 2011) of sea ice volume suggest a further decline of ice volume since 2007.

The above overview of model predictions (i.e., produced by GCM scenario simulations) and projections (i.e., resulting from the synthesis of GCM output with observations of sea ice) of a nearly ice-free Arctic Ocean and their limitations leads to an important conclusion. It suggests

a great need for improved understanding and model representation of physical processes and interactions specific to polar regions that currently might not be fully accounted for or are missing in GCMs. The remaining sections of this review are primarily focused on addressing those issues.

5. MODEL LIMITATIONS AND BIASES

There are many Arctic climatic processes that are omitted from, or poorly represented in, most current-generation GCMs. These processes include the following: oceanic eddies, tides, fronts, buoyancy-driven coastal and boundary currents, cold halocline, dense water plumes and convection, double diffusion, surface/bottom mixed layer, sea ice–thickness distribution, concentration, deformation, drift and export, fast ice, snow cover, melt ponds and surface albedo, atmospheric loading, clouds and fronts, ice sheets/caps and mountain glaciers, permafrost, river runoff, and air–sea ice–land interactions and coupling. As it is impossible to even briefly discuss the role of all these processes on regional climate here, this section focuses on the processes that we see as most critical in the prediction of Arctic sea ice.

One of the main processes that can directly affect the temporal evolution of Arctic sea ice volume is ice export from the Arctic through the Fram Strait and to a lesser degree into the Barents Sea (Kwok 2009). As an example, **Figure 10*a*** compares areal sea ice fluxes through the Fram Strait from two twenty-first-century CCSM3 ensemble runs with observational and NAME model fluxes. Whereas NAME model results are in good agreement with observational estimates both in the mean and in temporal variability, the CCSM3 sea ice areal fluxes through the Fram Strait are roughly twice as large [both during 2000–2004 (1.3×10^5 km^2 month^{-1} versus 0.65×10^5 km^2 month^{-1}) and for the long-term means (0.69×10^5 km^2 month^{-1} versus 1.2×10^5 km^2 month^{-1})]. This helps explain the excess of sea ice over the Greenland Shelf in CCSM3 (and in other models) as shown in **Supplemental Figure 1** (view the figure by following the **Supplemental Materials link** from the Annual Reviews home page at **http://www.annualreviews.org**), and it bears large consequences on the sea ice thickness and production as well as on the water mass properties and hydrological cycle of the Arctic Ocean.

Supplemental Material

Another factor affecting the sea ice export and distribution in the eastern Arctic is the northward oceanic heat flux via the West Spitsbergen Current and the Barents Sea. Northward volume and heat fluxes through the Fram Strait are compared in panels *b* and *c* in **Figure 10**, respectively. Here the situation is the opposite; both the volume and heat fluxes are approximately three times smaller in CCSM3 compared with the NAME model (roughly 2Sv versus 6Sv and 17 TW versus 45 TW). Northward flux estimates from available observations at the Fram Strait are $\sim 6.8 \pm 0.5$ Sv for volume and $\sim 36 \pm 6$ TW for heat flux (Beszczynska-Möller et al. 2011). Given that the transport of the West Spitsbergen Current is one of the main sources of salt and heat in the Arctic Ocean, discrepancies of a factor of three in its volume and property simulation are of great consequence both to sea ice and ocean. Oka & Hasumi (2006) investigated this particular GCM limitation in representing transports through the Fram Strait and found that increased spatial resolution in this region is a necessary requirement for improvement. They found that GCMs have problems with resolving two opposite-flowing currents (West Spitsbergen Current and East

Figure 10

Time series of Fram Strait fluxes. (*a*) The net sea ice–area flux (km^2 month^{-1}) from observations (*thick and thin green lines*; Kwok 2009), the NAME model (*thick and thin blue lines*), and CCSM3 [*thick and thin red lines* for CCSM3(b) and *thick and thin dark gray lines* for CCSM3(f)]. The thick lines represent annual running means. (*b*) The northward volume (Sv) and (*c*) heat (TW) fluxes, with the NAME model represented by blue lines and CCSM3 by red [CCSM3(b)] and dark gray [CCSM3(f)] lines.

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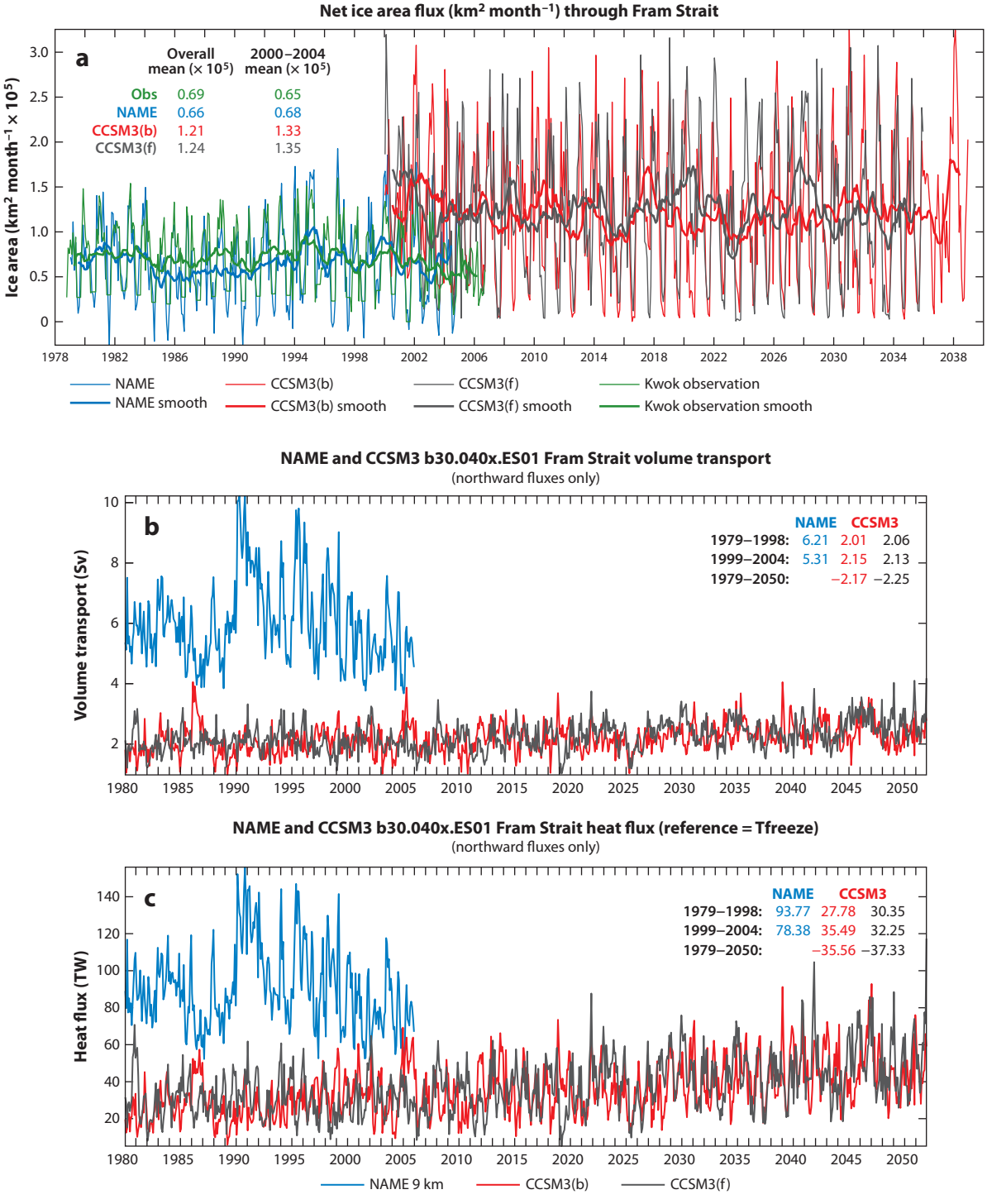

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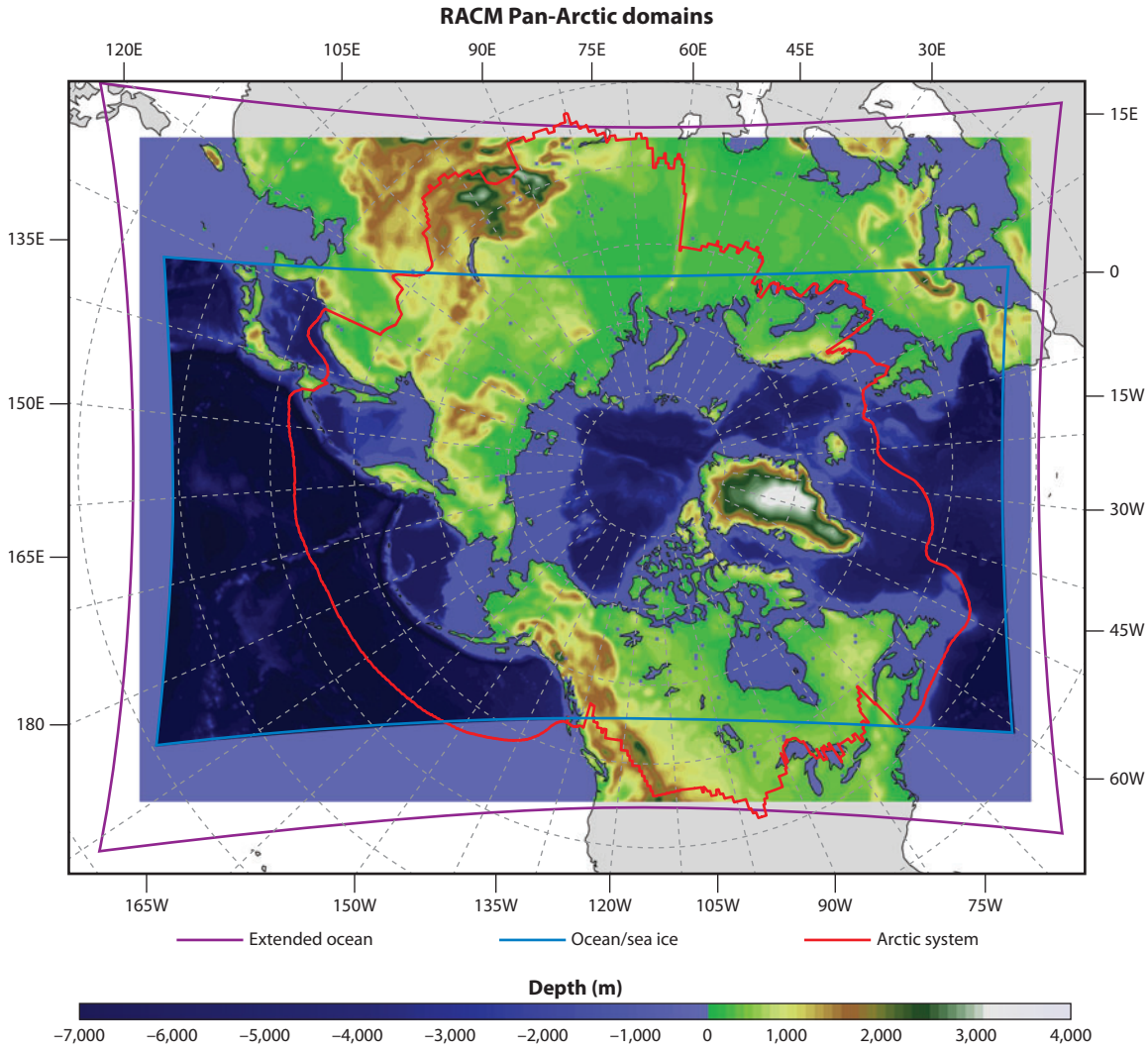

Figure 11

Pan-Arctic domains from the Regional Arctic Climate Model (RACM). The NCAR Weather Research and Forecasting model domains and the Variable Infiltration Capacity model domains include the entire colored region. Parallel Ocean Program and Community Ice Code model domains are bound by the inner blue rectangle. Shading indicates model topobathymetry. The Arctic system domain (*red line*) is as defined in Roberts et al. (2010).

Greenland Current) across this narrow strait, relative to typical global ocean model resolution, and instead have the flow dominated by the outflow from the Arctic Ocean.

The second path of Atlantic water into the Arctic enters via the Barents Sea, which is relatively wide yet shallow and is dominated by tides. **Table 1** lists the volume and heat transports calculated across the Barents Sea Opening (between Norway and Svalbard) and across a section between Franz Josef Land and Novaya Zemlya to capture outflow conditions. The net volume and heat transports from the literature (Maslowski et al. 2004, Gammelsrod et al. 2009) are 2.0–3.2 Sv and 29–162 TW, respectively, across the Barents Sea Opening, with a near-zero heat flux at the

Table 1 Volume (Sv) and heat (TW) fluxes (positive into the Arctic Ocean) through Fram Strait and Barents Sea from NAME and CCSM3 (ensemble b) models

	CCSM(b)						NAME					
	In		Out		Net		In		Out		Net	
Section	Volume	Heat	Volume	Heat	Volume	Heat	Volume	Heat	Volume	Heat	Volume	Heat
Fram Strait	2.0	17	−6.9	−23	−4.9	−6	6.0	45	−8.4	−36	−2.4	+9
Barents Sea Opening	4.8	115	−0.3	−5	4.5	110	5.0	107	−1.8	−28	3.2	79
FJL-NZ[a]	4.7	32	−0.35	−1	4.35	31	3.4	2.9	−0.8	−0.7	2.6	2.2

[a]FJL-NZ is the section between Franz Josef Land and Novaya Zemlya to capture outflow of Atlantic Water into the Arctic Ocean.

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outflow. It is estimated that 70–140 TW is lost to the atmosphere over the Barents Sea owing to water mass transformation through cooling and mixing. Whereas the NAME model shows similar fluxes and heat loss, CCSM3 significantly overestimates both the net volume and heat fluxes through and out into the Arctic Ocean. This results partly from insufficient recirculation within the Bear Island Through at the Barents Sea Opening (−0.3 Sv in CCSM3 versus −1.8 Sv in the NAME model) and inadequate flow in the Fram Strait branch. The narrow Norwegian Coastal Current (Maslowski & Walczowski 2002) and mesoscale eddies (Maslowski et al. 2008), which contribute to cooling of Atlantic water along the Barents Shelf, cannot be resolved with the spatial resolution currently typical in most global ocean models. Consequently, too much warm water enters the eastern Arctic Ocean, which causes excessive thinning, melt, and accelerated drift of sea ice, as shown in **Supplemental Figure 1** and argued by Rampal et al. (2011). Finally, reduced air-sea fluxes due to insufficient cooling of Atlantic water over the Barents Sea (between 70 and 140 TW) might be the primary reason for a large, positive SLP bias (~9 mb) centered over the Barents Sea reported in nearly all the GCMs of CMIP3 (Chapman & Walsh 2007).

Supplemental Material

Similar processes are also at play in the western Arctic, along the pathway of summer Pacific water. Inadequate model representation of the Alaska Coastal Current and mesoscale eddies in the Chukchi/Beaufort seas, and their role in the northward advection and redistribution of heat into and underneath the sea ice, might play an important role in realistic simulation of the ice edge and the reduction of sea ice area and thickness in this region (**Supplemental Figure 1** and **Figure 8**). This in turn may affect modeled sea ice drift and export (Rampal et al. 2011), as well as deformations.

There are also a number of important limitations in the way sea ice and ocean models are coupled in current-generation GCMs. Many vertical ocean coordinates do not allow the buoyancy force of sea ice to contribute to the barotropic mode (Griffies et al. 2004), even though ice buoyancy influences Ekman transport (e.g., Heil & Hibler 2002, Campin et al. 2008) and oceanic tides (e.g., Hibler et al. 2006). *Z*-coordinate models, for example, often represent freshwater exchange between sea ice and ocean as a virtual salt flux to avoid passing mass between them (Schmidt et al. 2004). Given the close relationship among sea ice drift, deformation, and pycnocline displacement via Ekman pumping (McPhee 2008), incorrect modeling of the combined ice-ocean Ekman layer may account for significant skill reduction in the modeled heat fluxes across the atmosphere-ice-ocean boundary. Moreover, incorrect ice-ocean dynamic coupling changes the friction velocity, u^*, which in turn changes ice-ocean heat flux. One GCM has addressed this problem by using a rescaled z^* coordinate system (Adcroft & Campin 2004, Campin et al. 2008), allowing mass to freely pass between sea ice and ocean models without thickness limitations on sea ice. Thermohaline coupling is also being refined in several models, as double diffusion at the ice-ocean interface can

significantly affect the heat budget across the entire sea ice column (McPhee 2008). Therefore, sea ice thermodynamic models are evolving to include false bottoms resulting from double diffusion at the ice-ocean interface (Notz et al. 2003) and underside mushy layers (e.g., Feltham et al. 2006).

In addition to changes in ice-ocean coupling, new sea ice mechanics and thermodynamics models are emerging to match the unprecedented resolution in regional Arctic models. Continuum mechanics assumptions stemming from the Arctic Ice Dynamics Joint Experiment (e.g., Hibler 1979) may be invalid at the high spatial resolutions now being achieved due to the inherent mechanical anisotropy of sea ice deformation (Coon et al. 2007). Anisotropy has previously been approximated with isotropic yield curves (e.g., Hutchings et al. 2005) but may be the cause of a mismatch between scaling characteristics of observed and modeled shear and divergence (Girard et al. 2009). A variety of different mechanics formulations have been proposed to replace the viscous plastic rheology (Hibler 1979) and elastic viscous plastic approximation (Hunke & Dukowicz 1997). These include elastic-decohesive constitutive models (Schreyer et al. 2006, Sulsky et al. 2007) and anisotropy approximate with scale-independent diamond-shaped floes (Wilchinsky & Feltham 2006), both of which offer promise for a better representation of multiscale mechanics. Perhaps the most significant improvement to basin-scale thermodynamics models since the introduction of enthalpy conservation (Bitz & Lipscomb 1999) has been the inclusion of melt ponds (e.g., Pedersen et al. 2009, Flocco et al. 2010). These are known to strongly affect albedo of the ice surface, especially during sea ice retreat. Work is ongoing to better understand sea ice–percolation thresholds (e.g., Pringle et al. 2009) and surface albedo characteristics (Polashenski 2011) that could soon be manifested in further improvements in melt-pond representation and thermodynamics in basin-scale sea ice models.

6. TRANSITION FROM GLOBAL CLIMATE MODELING TO HIERARCHICAL SYSTEM MODELING

For the past century, the analysis and modeling of the polar sea ice state have centered on the physical aspects of energy and mass fluxes between and within the ocean, sea ice, atmosphere, and terrestrial systems (e.g., Nansen 1902, Campbell 1965, Nikiforov et al. 1967, Maykut & Untersteiner 1971, Hibler 1979, Bitz et al. 2001, Serreze et al. 2006, Holland et al. 2010). However, persistent uncertainties and limited skill in high-north simulations are motivating research on a broader scope of problems to facilitate a better understanding of interconnectivity within the Earth system (Rind 2008, Doherty et al. 2009, Roberts et al. 2010). To that end, work is under way to (*a*) improve the fidelity and number of polar-centric processes represented within Earth system models, (*b*) refine coupling channels between them, and (*c*) expand the hierarchy of available models and observations to help quantify sources of uncertainty and skill in sea ice simulations. Much of this work is targeted toward understanding and improving sea ice–simulation metrics (uncertainty and skill) as leading indicators of our ability to predict the state of the Arctic.

Model development is being targeted toward physical and biogeochemical processes that are suspected of strong interconnectivity with the surface Arctic Ocean energy and mass budgets. These include marine and terrestrial biogeochemical and ecological processes with feedbacks to radiative forcing in the sea ice zone (e.g., Rysgaard et al. 2009, Zhang et al. 2010, Jin et al. 2011); cryospheric components with feedbacks to atmospheric and oceanic circulation, including the Greenland ice sheet, mountain glaciers (e.g., Bhatt et al. 2007), and permafrost evolution (e.g., Nicolsky et al. 2007, Lawrence et al. 2008); and refinements to sea ice–ocean models and their coupling (discussed in Section 5). Similar to the case of sea ice–ocean coupling, the degree to which sea ice interconnectivity can be realistically modeled with these new so-called Earth system components rests on the resolution, numerical treatment, and flux-exchange mechanisms along

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coupling channels. By increasing the number of interconnected processes in models, the degrees of freedom of the simulated Earth system expand, which poses problems for understanding causal climatic links, and is likely to increase model uncertainty in the next decade (Hawkins & Sutton 2009). For that reason, it is increasingly common for ad hoc one-dimensional models to be used to interpret output from complex global models (e.g., Merryfield et al. 2008, Eisenman & Wettlaufer 2009). This highlights a growing need for numerical tools that help explain Arctic interconnectivity and complexity on a regional basis, but in a global context.

Giorgi (1995) first advocated the development of regional Earth system models to generate probabilistic predictions that would be more useful to national and local decision makers than global model forecasts alone. Recently, a number of authors have stressed the need for high-fidelity regional ensemble projections (Challinor et al. 2009, Doherty et al. 2009, Moss et al. 2010). This is especially germane for the Arctic, where economic, social, and national interests are rapidly reshaping the high north in step with regional climate change (e.g., Arctic Council 2009, Proelss 2009). Roberts et al. (2010, 2011) proposed the creation of an ASM based around a core climate model configuration comprising an ocean circulation model, atmospheric model, sea ice model, and terrestrial model. So-called system components would be coupled to this core group and would include ice sheets and mountain glaciers (e.g., Bueler et al. 2011), dynamic vegetation (e.g., Smith et al. 2011), and ice-ocean biogeochemistry (e.g., Jin et al. 2011). Similar to the NAME model, ASMs can be constrained at their boundaries by observational data sets or analyses, filling an important gap in determining the relative contributions of regional and global contributions to the state of sea ice. However, they can also be constrained by GESMs to improve its prediction.

Owing to the limited area, ASMs can have substantially higher vertical and horizontal resolution, thus representing fine-scale Arctic processes that cannot be represented accurately in most current-generation global models, such as sea ice deformations, melt ponds, ocean eddies, and multiphase clouds. They can be used to span initial-value (weather) scales and boundary-value (climatic) scales, making them so-called unified models (Hurrell et al. 2009, Pielke 2010). Unified regional Arctic models provide a platform for understanding the influence of short-timescale regional physics, biogeochemistry, and ecological drivers of internal variability, in addition to longer-term shifts driven by changes both within the Arctic and at its boundary, as forced by a global model (e.g., Döscher et al. 2010).

Conversely, when the resolution of an ASM is not much greater than the global model that provides its boundary conditions, it can generate ensemble sizes prohibitive to its global counterpart, when not interactively nested (i.e., one-way nesting only). Uncertainty and skill could be further assessed with ASMs by using multimodel ensembles, similar to the methods used for European climate assessments (Deque et al. 2005). In doing this, sources of uncertainty can be attributed to internal variability of the Arctic, CO_2 emission scenarios, and both the regional model and the global model used to supply boundary conditions (Deque et al. 2005, Giorgi et al. 2008). Given that ASMs are now being developed in several countries (e.g., Dorn et al. 2007, Döscher et al. 2010), this method of uncertainty quantification may soon be possible for the Arctic sea ice cover. However, to do so, the domain of the Arctic system model must span a much greater area than just the sea ice zone. The proposed boundaries of the Arctic system by Roberts et al. (2010) are shown in **Figures 1** and **11** and are defined to include the "geosphere and biosphere north of the boreal mean decadal 10°C sea surface isotherm, the surface air 0°C contour that encircles the North Pole, and the southern limit of terrain that drains into the High Arctic." A regional model designed to estimate high-north climate uncertainties should arguably capture this entire region.

Future regional Arctic system models could potentially incorporate a multitude of geospheric and biospheric interactions that are not targeted presently. However, the goal is not to create an all-encompassing tool. Rather ASMs are intended to serve as tools that will enable researchers

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to break down complex interactions and explore regional coupling pathways in ways that are not possible in current global models. This approach can be further enhanced using an embedded ASM (Roberts et al. 2010) with global focused grids that allow it to be used either embedded in a global model or as a stand-alone regional Arctic model. This approach may also negate the need for ad hoc models to help explain complexity, variability, and change in global models. Meanwhile, one of the most important functions of ASMs is as a test bed for component models and coupling methods for next-generation Earth system models. Part of this process will involve evaluating the models against observations and working with observational networks to optimize deployments between the flagship site and distributed locations.

In an effort to address the need for an ASM in the United States, the Regional Arctic Climate Model (RACM) has been recently developed under the support of the Department of Energy Earth System Modeling program. The overarching goal of this multi-institutional collaborative project is to advance understanding of past and present states of Arctic climate and to improve seasonal to decadal predictions. The atmospheric model used in RACM is a version of the NCAR Weather Research and Forecasting model that has been optimized for the polar regions. The ocean and sea ice models are the same as those currently used in the NCAR CCSM4, although configured on a regional domain: the Los Alamos National Laboratory Parallel Ocean Program ocean model and Community Ice Code sea ice model. Land-surface processes and hydrology are represented by the Variable Infiltration Capacity model. These four component models are being coupled using the NCAR CCSM coupler CPL7. The RACM simulation domain covers the entire pan-Arctic region (**Figure 11**). It includes all sea ice–covered regions in the Northern Hemisphere as well as all terrestrial drainage basins that drain into the Arctic Ocean. For the baseline RACM, the ocean and sea ice models use a horizontal grid spacing of ~9 km, whereas the atmosphere and land component models use a horizontal grid spacing of ~50 km. Fully coupled RACM results are currently being evaluated for physical performance. Multidecadal integrations and tests with higher-resolution model configurations are under way as part of ongoing work.

A new project, expanding RACM into a regional ASM (RASM), will include ice sheets, ice caps, mountain glaciers, and dynamic vegetation to allow investigation of coupled physical processes responsible for decadal-scale climate change and variability in the Arctic. Currently, there are many GESMs, which are used to examine the past climate and predict future climate scenarios. However, as discussed above, GESMs are limited by relatively lower resolution, may lack various system components, and have large errors in representing northward fluxes of heat and moisture, sea ice distribution, and export of freshwater into the North Atlantic Ocean. RASM will ultimately have high spatial resolution (~5–50 times higher than currently practical in global models) to advance understanding and modeling of critical processes and determine the need for their explicit representation in GESMs. RASM research is focusing on the variability and long-term change of energy and freshwater flows through the Arctic climate system. The three foci of RASM are (*a*) changes in the freshwater flux between Arctic climate system components resulting from decadal changes in land and sea ice, seasonal snow, vegetation, and ocean circulation; (*b*) changing energetics due to decadal changes in ice mass, vegetation, and air-sea interactions; and (*c*) the role of small-scale atmospheric and oceanic processes that influence decadal variability.

7. FUTURE ADVANCEMENTS FOR IMPROVED ARCTIC SEA ICE PREDICTION

Sea ice is undergoing rapid decline; however, the skill in multimodel averages is relatively poor, the uncertainty in multimodel ensembles is large, and both are subject to model selection. Simple extrapolation from hindcasts sheds little light on the problem. Diagnosing the sources of simulation

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uncertainty is difficult because polar systems are tremendously complex, involving a myriad of geospheric, biospheric, and anthropospheric interactions at many scales. This presents difficulties in understanding sources of uncertainty, whether it derives from the nature of regional interactions, global interconnectivity, or models.

Global models have been steadily increasing their robustness, accuracy, and complexity roughly over the past two decades. The demand for output of such models has grown in parallel, providing a testimony to their success in addressing societal needs of climate relevance. A growing fraction of those needs requires regional and/or fine details in space and time, which has been commonly addressed through statistical or dynamical downscaling. Unfortunately, this approach does not improve inherent model limitations in the Arctic (discussed above) owing to a coarse-grid scale and subgrid parameterizations sensitive to those scales. Hence an alternative approach is the development of high-resolution limited-area ASMs interactively nested in or forced along the lateral boundaries by global models.

More recently, fine-resolution global climate configurations have been developed and tested (e.g., McClean et al. 2011). Those tests provide evidence that refining the spatial resolution of climate models improves the fidelity of their simulations. However, at least in the foreseeable future, the computational cost of running such ambitious applications will restrict their use. The computational cost will also limit progress with model improvements related to new space-dependent parameterizations, ensemble prediction, and limits of predictability. All this is especially true in the Arctic, where the finest possible spatial resolution is needed. Therefore, the development and use of high-resolution regional Arctic climate and system models and process-level subsystem models are important stepping stones in the coming decade for dedicated studies of regional processes and feedbacks, tests of new parameterizations and ensemble simulations, and the prediction of sea ice and other components of the Arctic System in a warming climate.

Another potential opportunity for advancing ASMs is under way with the development of a variable resolution or unstructured grid approach (Ringler et al. 2010; W.C. Skamarock, J.B. Klemp, M.G. Duda, L. Fowler, S. Park & T. Ringler, submitted manuscript), which shows great promise for bridging the gap and enabling high-resolution regional Arctic climate change exploration within the context of the global climate system model framework. At present, the dynamical core of the Model for Prediction Across Scales has been developed and is being tested at various stretched-grid formulations for the atmosphere and ocean. Subject to further progress with its development, an improved framework for robust regional Arctic climate system modeling might become available soon. Overall, these different modeling methodologies and results point to the ongoing need for a hierarchical approach to better understand the past and present states and estimate future trajectories of Arctic sea ice and climate.

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