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Key Points:
- Arctic sea ice is rapidly changing; thinning and summer extents are decreasing
- Changes are faster than model forecasts; feedbacks play a key role
- Changing sea ice is impacting biology and human activity in the Arctic

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Arctic sea ice in transformation: A review of recent observed changes and impacts on biology and human activity

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Abstract Sea ice in the Arctic is one of the most rapidly changing components of the global climate system. Over the past few decades, summer areal extent has declined over 30%, and all months show statistically significant declining trends. New satellite missions and techniques have greatly expanded information on sea ice thickness, but many uncertainties remain in the satellite data and long-term records are sparse. However, thickness observations and other satellite-derived data indicate a 40% decline in thickness, due in large part to the loss of thicker, older ice cover. The changes in sea ice are happening faster than models have projected. With continued increasing temperatures, summer ice-free conditions are likely sometime in the coming decades, though there are substantial uncertainties in the exact timing and high interannual variability will remain as sea ice decreases. The changes in Arctic sea ice are already having an impact on flora and fauna in the Arctic. Some species will face increasing challenges in the future, while new habitat will open up for other species. The changes are also affecting people living and working in the Arctic. Native communities are facing challenges to their traditional ways of life, while new opportunities open for shipping, fishing, and natural resource extraction. Significant progress has been made in recent years in understanding of Arctic sea ice and its role in climate, the ecosystem, and human activities. However, significant challenges remain in furthering the knowledge of the processes, impacts, and future evolution of the system.

1. Introduction

The Arctic is a region in transition to a warmer climate, and one of the most visible signs of that change is in the declining sea ice cover. Ice extent has decreased in all months over the past 30+ years, particularly during summer, reaching levels that likely have not been seen in several thousand years. The ice cover is also thinning and becoming more dominated by thinner, younger ice types. The decline in extent is faster than most models have forecast, leading to possible near ice-free summer conditions sometime in the coming decades. Feedback mechanisms are accelerating the loss of ice although there are some negative feedbacks that may slow the loss. The declining sea ice is already impacting Arctic ecosystems and humans living and working in the Arctic. It is expected that these impacts will grow and broaden as the loss of sea ice continues.

Sea ice is defined as ice that grows and melts within ocean waters. Ice formation is primarily thermodynamically driven, but ice may also thicken via dynamic redistribution of the ice cover from ice motion and deformation. Much of the ice cover drifts in response to wind and ocean current forcing, density gradients in the ocean surface, and the Coriolis effect. Divergent motion of the ice opens up linear cracks in the ice, called leads, within the ice pack. Convergent motion deforms ice into ridges that may be several meters thick. In many places near the coast, nondrifting landfast, or simply "fast," ice grows anchored along the shoreline and/or shallow shelf waters. On lee sides of coasts, ice shelves, or fast ice, persistent winds can keep regions ice-free for long periods of time even in winter as winds continually push ice away from stationary features. These open water regions, called polynyas, typically recur regularly in certain locations; some polynyas may also form due to upwelling of warm ocean waters to the surface.

Table 1. Selected Publicly Accessible Sources of Arctic Sea Ice Extent Data From Passive Microwave Satellite Sensors[a]

Group	Website
Arctic Regional Ocean Observing System, Nansen Environmental Remote Sensing Center, Bergen, Norway	http://www.Arctic-roos.org/
The Cryosphere Today, University of Illinois at Urbana-Champaign, Urbana, Illinois, USA	http://arctic.atmos.uiuc.edu/cryosphere
NASA Goddard Sea Ice Remote Sensing	http://polynya.gsfc.nasa.gov/seaice_datasets.html
University of Bremen	http://www.iup.uni-bremen.de/seaice/amsr/
Japanese Space Exploration Agency	http://www.ijis.iarc.uaf.edu/en/home/seaice_extent.html
Danish Meteorological Institute Center for Ocean and Ice	http://ocean.dmi.dk/arctic/icecover.uk.php
Sea Ice Index, National Snow and Ice Data Center, University of Colorado Boulder, Boulder, Colorado, USA	http://nsidc.org/data/seaice_index/

[a]The extent estimates quoted in this paper are from the Sea Ice Index.

Sea ice represents the interface between the ocean and the atmosphere and thus substantially modifies heat, moisture, and momentum fluxes at the surface. In addition, it is a unique ecosystem that numerous species have adapted to over the millennia. Humans also interact with the sea ice environment in a variety of ways. Native communities in the Arctic have long relied on sea ice as a platform for hunting, fishing, and transportation. Sea ice is an impediment and/or threat to many commercial activities in and around the Arctic, including shipping, fishing, tourism, and natural resource extraction.

Arctic sea ice coverage varies considerably with season, reaching a maximum areal extent in late February or March and declining through the spring and summer to a seasonal minimum extent in September. At its maximum extent, sea ice coverage can reach well south of areas typically considered "Arctic" to the northern coast of Japan in the Sea of Okhotsk and the southern portions of the Canadian Maritime Provinces. At its minimum extent, the sea ice cover largely retreats to within the boundaries of the Arctic Ocean proper.

In 2011, the Snow, Water, Ice, Permafrost in the Arctic (SWIPA) Assessment Report [*Arctic Monitoring and Assessment Programme*, 2011], with contributions from over 200 scientists and experts, was released, including a comprehensive review of sea ice conditions and impacts [*Meier et al*., 2011]. However, the Arctic is rapidly changing, and recent observations and research are revealing new aspects of the sea ice cover.

Here we update the sea ice chapter of the SWIPA report with summaries of research and data that have accumulated since the drafting of the report in 2009. This review and update follows a similar organization as the SWIPA report. Section 2 describes the observed physical changes and model simulations of the historical changes and projections for the future state of the sea ice cover [*Meier and Haas*, 2011], including feedbacks and thresholds in the sea ice system [*Perovich and Makshtas*, 2011]. Section 3 presents results on the biological impacts of changes in sea ice in the Arctic [*Kovacs and Michel*, 2011]. Section 4 elucidates the effects of sea ice change on human society [*van Oort et al*., 2011]. Finally, we provide a brief summary, including discussion of potential impacts of sea ice change beyond the Arctic.

2. Changes in the Physical State of Sea Ice

2.1. Changes in Sea Ice Extent and Concentration

The spatial coverage, time period, frequency, and quality of sea ice data varies over time depending on parameter and type of measurement. The most complete sea ice observations exist for sea ice extent (defined here as areal coverage with at least 15% ice coverage) based on a series of satellite-borne multichannel passive microwave radiometers beginning in late 1978. Careful intersensor calibration and quality control have enabled the production of consistent time series of basin-scale and regional extents. Several algorithms have been developed to retrieve sea ice extent estimates and time series and several products can be obtained from different organizations (Table 1). There are some important differences in the products (as described by *Andersen et al*. [2007] and *Meier* [2005]), but there is good overall consistency in estimates of long-term trends and variability. The sea ice extent/concentration imagery and total extent statistics quoted here are derived from passive microwave imagery using the NASA Team sea ice concentration algorithm [*Cavalieri et al*., 1996, 1999; *Maslanik and Stroeve*, 1999; *Cavalieri and Parkinson*, 2012], distributed by the National Snow and Ice Data Center's Sea Ice Index (http://nsidc.org/seaice_index/; [*Fetterer et al*., 2002]).

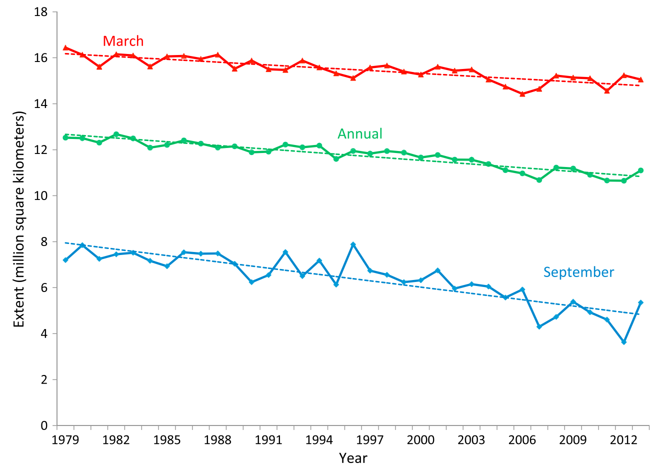

Figure 1. Time series of monthly average total extent (solid lines) for March (red), September (blue), and the annual average (green) for 1979–2013 and linear trend (dotted lines).

Total Arctic sea ice extent shows a declining trend through all months over the passive microwave satellite record since 1979, with the smallest trends in March and the largest trends in September (Figure 1 and Table 2). The downward trends are larger in magnitude over the past decade, indicating an acceleration in ice loss due to feedback mechanisms, natural decadal variability, or a combination of the two.

The decline during summer has been particularly striking over the past decade. Of the 34 years in the passive microwave record, the nine lowest September extents have occurred in the last 9 years of the record (2004–2013). While September has the largest declining trends, other summer and early autumn months also have significant trends of −6% decade^{-1} or steeper. All trends are statistically significant at the 99% confidence level. September concentration (fractional area coverage) has also been low over the past several years in much of the ice-covered areas, though some areas have positive concentration anomalies, mostly due to local convergent ice motion packing the ice more tightly (Figure 2).

The extent decline is pan-Arctic with almost all regions of the Arctic showing statistically significant decreasing trends during months where ice cover in the given region can vary (i.e., not completely ice-covered or completely ice-free). The primary exception is in the Bering Sea during winter and spring (December–May) where trends are positive or not statistically significant at the 95% confidence level [*Cavalieri and Parkinson*, 2012; *Meier and Haas*, 2011].

Estimates of sea ice extent before the passive microwave record become increasingly sparse through the preceding decades. Such estimates that exist for the Arctic are primarily from operational ice charts produced by national ice analyses centers, particularly in Russia, Canada, and the United States. These charts were produced to support shipping and other human activities in the Arctic and were based primarily on ship reports, aircraft reconnaissance, and, starting in the 1960s, early satellite imagery. Some analyses date back to

Table 2. Average Extent and Trends for March, September, and the Annual Average[a]

	March	September	Annual
1979–2013 average (10^6 km^2)	15.49	6.40	11.76
1979–2000 average (10^6 km^2)	15.75	7.04	12.13
2001–2013 average (10^6 km^2)	15.06	5.33	11.14
1979–2013 trend (km^2 yr^{-1})	−39,500	−89,100	−52,600
1979–2000 trend (km^2 yr^{-1})	−40,600	−48,900	−36,600
2001–2013 trend (km^2 yr^{-1})	−34,700	−171,000	−72,700
1979–2013 trend (% decade^{-1})	−2.5	−12.7	−4.3
1979–2000 trend (% decade^{-1})	−2.6	−6.9	−3.0
2001–2013 trend (% decade^{-1})	−2.2	−24.3	−6.0

[a]Estimates are provided for three periods: the entire 1979–2013 time series, 1979–2000, and 2001–2013. For consistency, the % decade^{-1} trends are all relative to the 1979–2000 average.

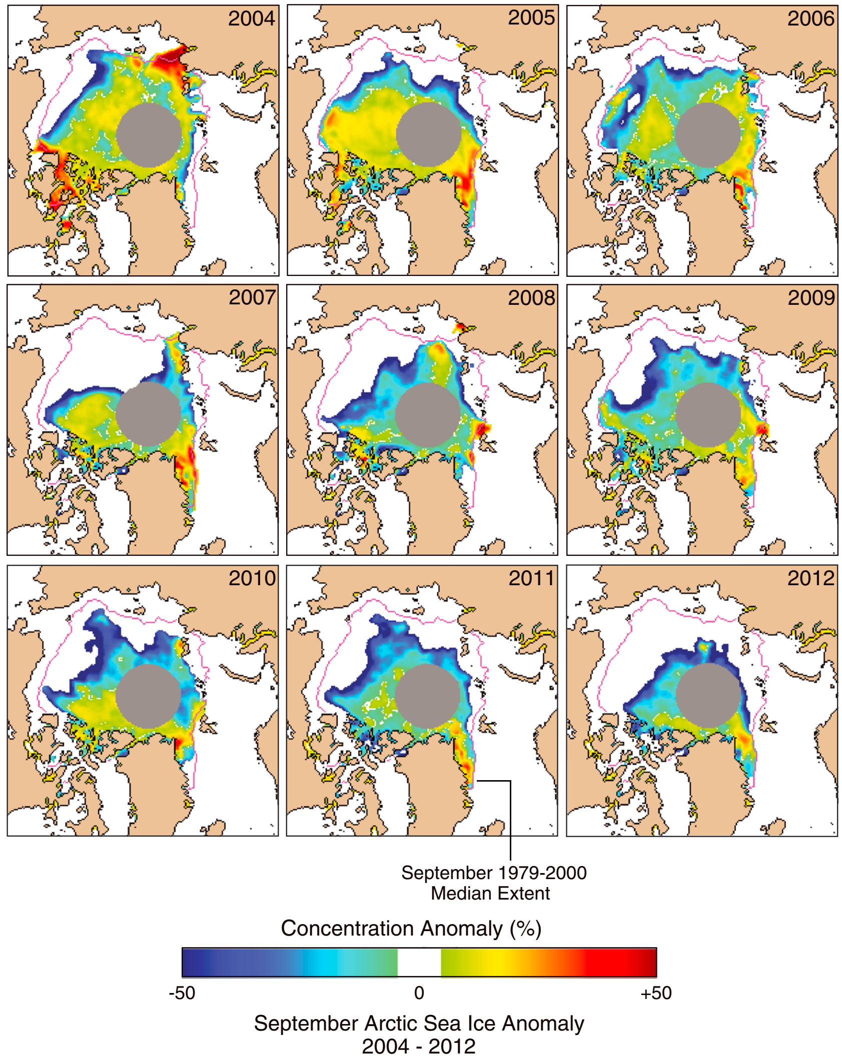

Figure 2. September sea ice concentration and extent anomaly maps for 2004–2012. The gray circle indicates the region not covered by some sensors over the 1979–2012 period due to orbit and sensor instrument limitations. Anomalies are relative to the 1979–2000 average.

the late 1920s, but hemispheric did not start until the early 1950s. These analyses indicate reduced concentrations in some regions at some times of the year during the warm period of the Arctic in the 1930s and 1940s, but confirm that the current basin-wide decline is unique over the past 80 years in terms of magnitude and regional and seasonal characteristics [*Titchner and Rayner*, 2014; *Tivy et al.*, 2011; *Mahoney et al.*, 2008; *Walsh and Chapman*, 2001]. A normalized monthly trend using a homogenized pre-satellite and satellite record since 1953 indicates that the current decline began in the early 1970s [*Meier et al.*, 2012].

Before the observational record, we must rely on proxy data from tree rings, ice cores, and sediment cores. This is a rapidly evolving field, and recently, there have been several new paleo-records of ice conditions from locations all around the Arctic [e.g., *Halfar et al.*, 2013; *Stein and Fahl*, 2013, and references therein], especially through the use of a novel biomarker approach [*Belt et al.*, 2007] in combination with other proxies [*Stein and Fahl*, 2013]. Some records suggest multidecadal variability in the Atlantic sector that appears to be related to the Atlantic Multidecadal Oscillation [*Miles et al.*, 2014]. However, available proxy records provide indirect evidence that current pan-Arctic ice conditions are low compared to historical levels and the recent change is unprecedented at least over the past few thousand years [e.g., *Polyak et al.*, 2010; *Kinnard et al.*, 2011; *Halfar et al.*, 2013]. Results from a pan-Arctic multiproxy study links multidecadal sea ice variability

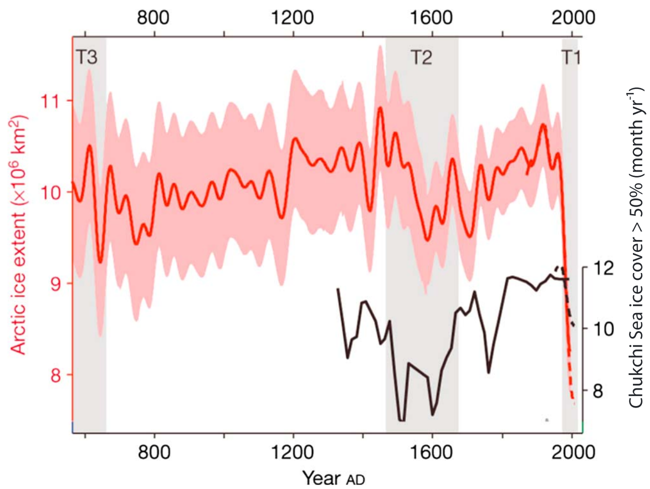

Figure 3. Paleo time series of (top) Arctic sea ice extent and (bottom) Chukchi Sea ice seasonal persistence (concentration greater than 50%) from proxy (561–1995) and observations with other climate indicators. T1–T3 highlight periods of reduced sea ice coverage. Adapted from *Kinnard et al*. [2011, Figure 3].

over the past 1450 years to the advection of warm Atlantic water, with the anthropogenic warming an important factor in the decline over the most recent decades [*Kinnard et al*., 2011] (Figure 3). Reconstructions from proxy records place the current decline in a longer-term climate context, and as new methods and when more proxy data are collected and analyzed, the pre-twentieth century Arctic sea ice conditions will come into better focus, and we can put the current changes into longer-term context.

2.2. Changes in Sea Ice Thickness

Along with sea ice extent and concentration, thickness is an essential component of the sea ice mass balance. Unfortunately, observations of thickness are much more limited due to sparse spatial and temporal coverage and/or uncertainties in measurements. Only in the last decade, with the emergence of satellite data from the cryospheric-focused altimeters Ice, Cloud, and land Elevation Satellite (ICESat) and CryoSat-2, has the sea ice thickness distribution been mapped throughout the Arctic [*Giles et al*., 2008; *Kwok and Rothrock*, 2009; *Laxon et al*., 2013]. Thickness estimates from ICESat indicated a substantial thinning of multiyear ice between 2003 and 2008 of ~0.5 m, but little change in first-year ice thickness [*Kwok et al*., 2009]. Cryosat-2 data are now providing basin-scale estimates of thickness and indicate a continued thinning since ICESat measurements and a considerable loss of thick ice along the northern coast of Greenland and Canadian Archipelago [*Laxon et al*., 2013] (Figure 4). The CryoSat-2 estimates agree well with model estimates from the Pan-Arctic Ice Ocean Modeling and Assimilation System sea ice model [*Schweiger et al*., 2011]. However, challenges remain because the observations are indirect (measuring freeboard, not thickness),

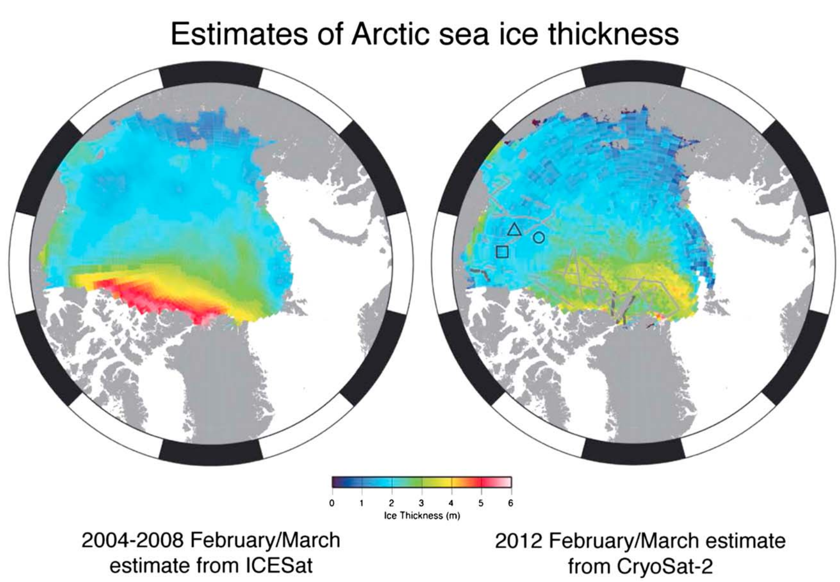

Figure 4. Sea ice thickness maps for February/March, (left) 2004–2008 average from ICESat and (right) 2012 from CryoSat-2 with location of validation data from ULS moorings (triangle, circle, and square) and airborne missions (gray and black lines). Adapted from *Laxon et al*. [2013].

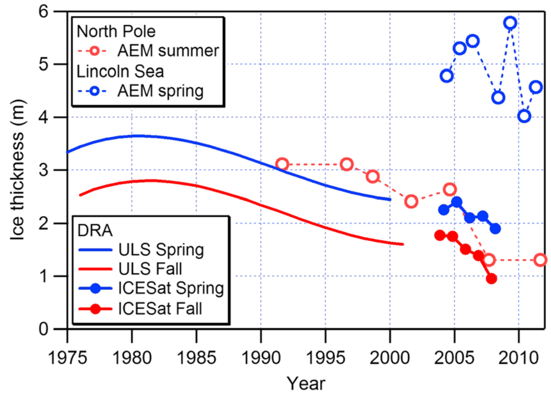

Figure 5. Sea ice thickness changes in spring (February–March) and fall (October–November) from 1975 to 2011 from submarine ULS, ICESat laser altimeter, and airborne electromagnetic induction (AEM) observations. The submarine and ICESat laser estimates averaged over much of the central Arctic basin while the AEM are from near the North Pole and the Lincoln Sea, a region north of Greenland where ice is typically thicker than the basin average due to advection and compaction of ice. Figure adapted and updated from *Kwok and Rothrock* [2009] and *Haas et al.* [2008].

and hampered by substantial uncertainties as detailed in *Kwok* [2010]. These include uncertainties in snow cover [e.g., *Forsström et al.*, 2011] (see section 2.3), ice density [*Zygmuntowska et al.*, 2014], and reconciling the radar (from CryoSat-2) and laser (from ICESat) altimeter measurements without overlap between sensors. Airborne campaigns, such as the NASA Operation IceBridge mission [*Koenig et al.*, 2010] and several European campaigns [e.g., *Haas et al.*, 2010], have been undertaken to collect data over sea ice that will bridge ICESat, CryoSat-2, and the future ICESat-2 (launch planned in 2016 or 2017) and provide validation data in key areas of the Arctic [*Farrell et al.*, 2012; *Kwok et al.*, 2012].

The best long-term record of the changes in the ice thickness distribution in the Arctic stem from a combination of observations, primarily from upward looking sonar (ULS) on submarines. Submarine platforms have collected data under the ice since the 1950s and continue in sporadic campaigns [e.g., *Wadhams et al.*, 2011], while moored ULSs in the Fram Strait have recorded ice thickness for two decades [*Hansen et al.*, 2013]. However, release of data from submarines has been limited and slow due to national security constraints and coverage and sampling are limited. Nonetheless, submarine data provide the most complete picture of ice thickness from the 1950s through the mid-1990s. A compilation of submarine data indicates a general decline from the mid-1970s through the 1990s that continued and accelerated in the ICESat era [*Kwok and Rothrock*, 2009]. Overall, central Arctic winter (February–March) mean thickness was reduced from 3.64 m in 1980 to 1.89 m in 2008 (Figure 5).

In the last decade or so, autonomous ice mass balance buoys [e.g., *Jackson et al.*, 2013; *Richter-Menge et al.*, 2006] have been deployed, providing information on ice drift and thickness evolution, especially quantifying bottom and surface melt [*Perovich et al.*, 2014]. In situ observations (drillings), which provide a direct measurement of the ice thickness, provide limited information as they are limited in time and space, but can provide valuable local information and data sets to validate remotely sensed data [e.g., *Alexandrov et al.*, 2010]. The trends from submarine and satellite data have been confirmed in selected regions by these in situ measurements and from airborne instruments. For example, modal ice thickness near the North Pole, estimated from ground and airborne electromagnetic (EM) induction measurements, dropped from ~3 m in 1991 to just over 1 m in 2007 [*Haas et al.*, 2008] and continued to be thin through 2011. The longest continuous instrumental record of Arctic pack ice thickness, from the Transpolar Drift in Fram Strait (1990 to 2011), also shows considerable thinning, the annual mean ice thickness was about 3.0 m in the 1990s, and it had decreased to about 2.2 m in 2008–2011, with most of the thinning taking place after 2005–2006 [*Hansen et al.*, 2013]. However, measurements from the Lincoln Sea, off the northwest coast of Greenland, do not show a significant thinning in recent years. This is due to continued advection of ice toward the coast resulting in dynamic thickening (ridging) of the ice. The contrast in the two locations highlights the regional variability in the ice thickness distribution and the importance of dynamics in the evolution of ice thickness.

Estimates of sea ice thickness, at least up to a certain threshold, are now being retrieved from the radiative properties measured by some instruments. Infrared radiation is an indication of the heat flux from the ocean, which is modulated by the thickness of the overlying ice cover. The albedo of thin ice also indicates thickness because the ice becomes lighter as it forms and thickens. Generally, visible and infrared methods based only on temperature or albedo are limited to relatively thin ice because any "signal" from the ocean is lost as the ice thickens and becomes snow covered. However, using cloud and surface properties derived from visible and infrared data combined with a thermodynamic growth model, *Wang et al.* [2010] obtained basin-wide thickness estimates up to 2.8 m with a mean error of 11% relative to in situ thickness data. A similar approach to characterize thin (less than 30 cm) versus thick sea ice is used with the Visible Infrared Imaging Radiometer Suite on the Suomi National Polar-orbiting Partnership satellite [*Key et al*., 2013]. Passive microwave emissions at 1.4 GHz from the European Space Agency Soil Moisture and Ocean Salinity (SMOS) instrument, launched in 2009, have retrieved thickness estimates for sea ice up to 0.5 m [*Huntemann et al*., 2014; *Kaleschke et al*., 2012].

Thus, while there are myriad measurement techniques of sea ice thickness, the data are of varied spatial and temporal resolution and coverage, the methods retrieve different observable parameters (draft, ice freeboard, snow + ice freeboard, or total thickness), and there are significant challenges in integrating the data into a cohesive product that could be used for long-term observations and model validation [*Schweiger et al*., 2011; *Johnson et al*., 2012]. The development of comprehensive observations of sea ice thickness from satellite data is one of the significant achievements in sea ice research over the past decade. However, there is still work needed to lower uncertainties, intercalibrate between different sensors, and integrate with pre-satellite data to yield a consistent long-term record of ice thickness change. Unfortunately, many of the pre-satellite measurements from in situ, EM, and moored ULS platforms have been collected by individual researchers on field expeditions, and there are no common data collection or even data processing standards. A recently started project aims to meet these needs [*Lindsay*, 2013], but many records are still not being shared and integration remains a challenge.

2.3. Snow on Sea Ice

Snow is an essential part of the sea ice system and plays a crucial role in the evolution of the ice cover. In addition, it is an important factor affecting observations of sea ice and must be properly accounted for. Snow insulates the sea ice surface from the atmosphere above, slowing ice growth during the winter and delaying ice melt during summer. The onset of melt of the snow cover significantly changes the radiative balance of the surface, with albedo dropping from ~0.8 for cold, dry snow to 0.5 or less for ponds of melted snow on the ice [e.g., *Perovich and Polashenski*, 2012]. Snowmelt also significantly affects the retrieval of sea ice concentration from passive microwave data because the emission properties change significantly with the change in phase. Finally, information on snow depth and density is key to retrieving accurate ice thickness measurements because other than drill holes, all thickness techniques measure a quantity that snow affects or to which it is a significant contributor of uncertainty. Altimeters measure freeboard, which is affected by the weight of the snow, and laser altimeters actually measure from the snow surface, so the snow depth must be explicitly accounted for to calculate a total ice thickness. ULS instruments measure draft, so snow depth and density is an uncertainty in converting the draft measurements to total thickness.

Despite the importance of snow, there is little observational data due to the difficulties in obtaining long-term comprehensive data sets in the Arctic Ocean. Existing basin-scale information comes from climatologies based on sporadic in situ measurements [*Warren et al*., 1999], passive microwave data over limited regions and with high uncertainties [e.g., *Brucker and Markus*, 2013], or estimated from precipitation fields in atmospheric reanalyses. Airborne surveys from NASA's Operation IceBridge using a snow radar system during 2009 found that while multiyear snow depths were similar to climatological values over 1954–1991 [*Farrell et al*., 2012; *Kwok et al*., 2011; *Kurtz and Farrell*, 2011], snow depth on first-year ice was considerably lower [*Kurtz and Farrell*, 2011]. These measurements were limited to a western Arctic region extending from northern Greenland to Point Barrow, Alaska. On the other hand, *Haapala et al*. [2013] found that snow depths on first-year ice, north of Svalbard, were close to *Warren et al.* [1999] climatology, and much higher on deformed ice. Thus, there may be large regional and interannual variations, which are currently difficult to account for. A comprehensive, high-quality, basin-scale snow cover on sea ice data product is a major gap in current observational capabilities of the Arctic sea ice cover.

2.4. Changes in Sea Ice Age and a Transition Toward a Seasonal Ice Cover

Because the observational record of sea ice thickness is sparse, short, and/or limited by high uncertainties, data from which one can infer thickness are an important contribution toward tracking changes in sea ice thickness. Ice age is just such a parameter because sea ice largely grows thermodynamically over time, and generally speaking, older ice is thicker ice up to the point when an equilibrium thickness, usually 3–4 m, is reached based on ocean and atmospheric temperatures. This assumption ignores the effects of dynamic

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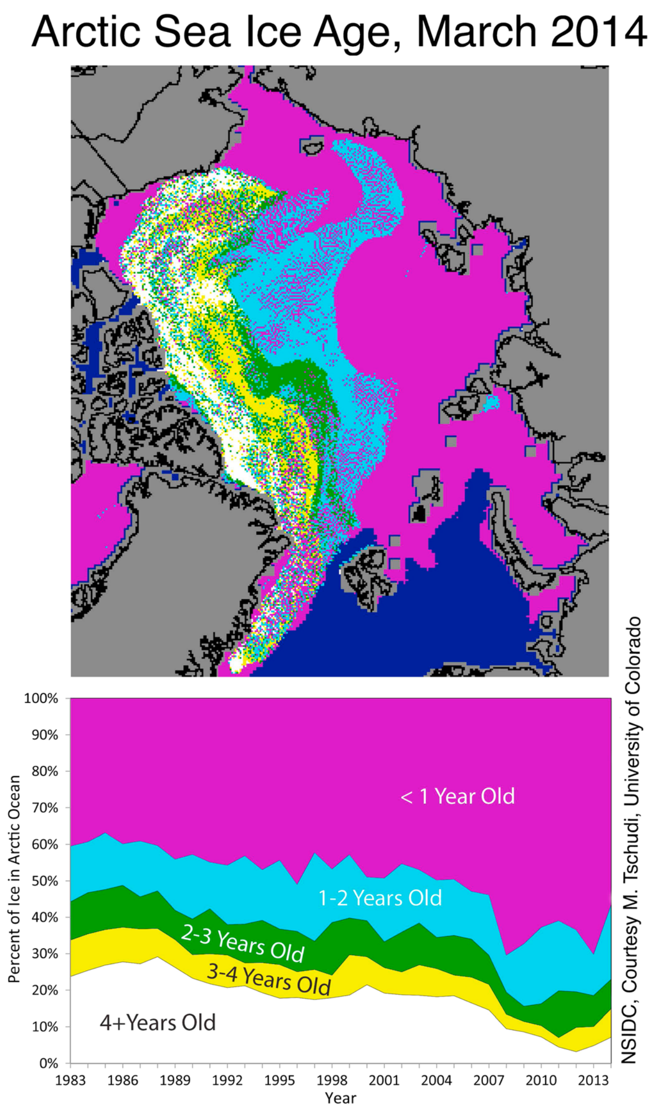

Figure 6. Ice age field for March 2014 (top) and time series of areal composition of March ice age types for 1983–2014. Data from J. Maslanik and M. Tschudi, University of Colorado Boulder, updated from *Maslanik et al*. [2007]. Image from National Snow and Ice Data Center (NSIDC) Arctic Sea Ice News and Analysis, April 2014, http://nsidc.org/arcticseaicenews/.

thickening (ridging/rafting), which can lead to large errors locally. However, over the entire basin, tracking changes in the age of the ice can provide a useful proxy indication of changes in ice thickness.

One approach estimates the presence of multiyear or first-year ice from microwave radiometric properties using passive microwave or scatterometer sensors based on the difference in salinity between the two types of ice (first-year ice traps saline water during freeze-up, much of which drains during the following melt season before the ice ages to the multiyear category) [*Nghiem et al*., 2012]. Another approach to estimate ice age is to track the motion of the ice over time, using feature-matching techniques in satellite images or buoy position data. As the ice drifts with the winds and currents, the age of Lagrangian parcels of ice is recorded. This approach can not only distinguish between first-year and multiyear ice but as many age categories as one wishes after a required initialization period to accumulate a long enough record (e.g., 3 years of data are needed to distinguish ice that is 3+ years old).

Both approaches show a clear trend of declining multiyear ice since the late 1970s when continuous microwave satellite data became widely available and buoy deployments began. The decline has been particularly sharp in the past decade, with a decline in end-of-summer multiyear ice area from over 3.0 million km^2 in 2000–2006 to under 2.0 million km^2 in 2008 [*Kwok et al*., 2009], based on scatterometer-derived estimates. This is consistent with the above mentioned observed thinning of the ice cover observed by ICESat during 2003–2008. Ice age from Lagrangian tracking also corroborates these findings and provides a longer term context (Figure 6). In the mid-1980s, multiyear ice comprised 50% of the winter ice area; now it is less than 30% and the oldest ice types (4+ years old) have nearly disappeared [*Maslanik et al*., 2011]. Thus, multiple lines of evidence (satellite thickness estimates, in situ and airborne observations, and ice age estimates) all point to a thinning ice cover dominated by seasonal ice.

However, it is important to note that there is substantial interannual variability, and indeed, the ice age data indicate some recovery of the area of older ice since a low in 2008; though as the ice ages through subsequent years, the recovery in the older types is becoming smaller (Figure 6). One reason for this appears to be increased summer melt of multiyear ice [*Stroeve et al*., 2011], further suggesting a regime shift toward a seasonally ice-free Arctic Ocean.

2.5. Observed Changes in Other Sea Ice Parameters

One of the factors contributing to the thinning of the ice cover and the loss of summer ice extent is an earlier onset of melt. When melt begins, albedo (discussed further below) drops significantly allowing greater absorption of solar radiation. A significant trend toward earlier melt has been found from passive microwave satellite data [*Stroeve et al*., 2014a; *Wang et al*., 2013]. From 1979 to 2013, the onset of melt has trended earlier by an average of 5 days decade^{-1} [*Stroeve et al*., 2014a], corresponding to an average melt onset date about 2 weeks earlier than in 1979; some regions have experienced even larger trends of up to 11 days decade^{-1} earlier melt onset. The earlier sea ice melt correlates well with earlier melt of snow on land and increasing air temperatures.

Sea ice motion is another important factor in the evolution of the sea ice cover through advection of ice within the Arctic and transport of ice out of the Arctic, primarily through Fram Strait, and redistribution of ice thickness via rafting, ridging, and lead/polynya formation. There has been an increasing trend in sea ice drift speed since 1992 [*Smedsrud et al*., 2011], which is not captured by models [*Spreen et al*., 2011]. The overall trend in speed is 10.6% ± 0.9% decade^{-1}, with a range of −4% to 16% decade^{-1} depending on location. An increase in ice deformation rates from synthetic aperture radar data has also been noted [*Herman and Glowacki*, 2012]. *Kwok* [2011] compared the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) model estimates of ice motion, export through Fram Strait, and thickness with observations and found large discrepancies due to significant displacement of dominant atmospheric circulation patterns that drive large-scale ice motion (e.g., the Beaufort Gyre and Transpolar Drift Stream). *Rampal et al*. [2011] also showed large differences between model estimates and observations with the models underestimating the speed of sea ice. The underestimation is not attributable to changes in wind forcing, but rather to a thinner ice cover that is more easily advected by winds. In modeling studies, thinner ice was found to lead a decrease in mechanical strength, and an increase in surface stress [*Martin et al*., 2014] resulting in faster ice speed and greater deformation [*Gimbert et al*., 2012; *Zhang et al*., 2012]. This suggests the potential for both positive and negative dynamic feedbacks in the sea ice system (sea ice feedbacks are discussed in detail in section 2.7).

In particular, the enhanced response to wind forcing by the thinner and younger ice cover makes the ice more vulnerable to extreme events such as the strong cyclone that tracked across the Arctic Ocean in early August 2012 [*Simmonds and Rudeva*, 2012]. While the event was an extremely deep low-pressure system for the time of year, the thinner, weaker ice cover was a key factor in the rapid ice loss following the storm [*Parkinson and Comiso*, 2013; *Zhang et al*., 2013]. Cyclone activity may have also influenced other low extent years between 2007 and 2012 [*Kriegsmann and Brümmer*, 2014].

2.6. Comparison of Model Output With Observational Data

In recent years, there has been growing interest in predicting and projecting the future state of ice cover on seasonal, decadal, and century timescales. Seasonal prediction requires physical models or statistically based models using past correlations between winter and spring conditions and summer extent. Projection of the future state of the Arctic sea ice cover over the next decades and centuries necessarily requires physical sea ice models [*Overland et al*., 2011]. Here we compare modeling studies of future sea ice states with observed changes.

The changing ice cover is impacting wildlife and native populations in the Arctic and opening up opportunities for increased human activities in the Arctic. These impacts are discussed in sections 3 and 4. These changes are spurring a desire for improved seasonal predictability of the Arctic. To a large extent, attempts at seasonal forecasting have been ad hoc with researchers investigating independently [e.g., *Sigmond et al*., 2013; *Kauker et al*., 2009], though efforts at coordination are developing through the Study of Environmental Arctic Change Sea Ice Outlook (http://www.arcus.org/search/seaiceoutlook). A significant problem with seasonal forecasting is the lack of accurate initial conditions, particularly ice thickness (though the new airborne and satellite data discussed above are beginning to address this deficiency [*Kurtz et al*., 2013]), and inherent uncertainty in summer weather conditions. Outlooks for 2012 substantially overestimated the minimum ice extent [e.g., *Lindsay et al*., 2012] while the 2013 extent was underestimated; overall, it appears that years with minimum extents that substantially vary from the long-term trend are difficult to predict [*Stroeve et al*., 2014b]. The varied skill of the predictions is due to the large variability in

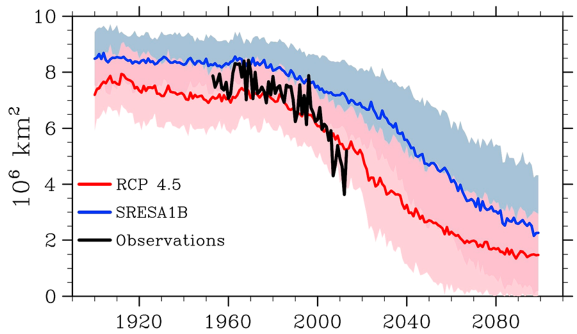

Figure 7. IPCC AR4 A1B and AR5 RCP4.5 model projections for September sea ice extent, 1900–2100, and observations from 1953 to 2013. Adapted from *Stroeve et al*. [2012].

summer weather conditions, as well as uncertainties in initial conditions and limitations in the models. A recent paper shows that the timing and extent of melt ponds have predictive skill on the summer minimum, suggesting that seasonal forecasts can be improved with relevant initial data [*Schröder et al*., 2014].

Decadal projections are also of interest for long-range planning, but these also entail considerable uncertainty due to strong interannual natural variability that can outweigh the long-term forcing. Model simulations indicate that internal variability may account for half of the observed trend, and there is a possibility over the next century of decadal periods or even longer with positive trends in sea ice extent, even under greenhouse gas forcing [*Kay et al*., 2011]. One of the difficulties with decadal projections is that their timescales fall between the influence of initial conditions and the long-term forcing. Some predictability has been found for up to 3–4 years from initial conditions (particularly if the ice thickness distribution is well known), but beyond that only climate forcing—both natural variability and long-term greenhouse gas forcing—has an influence on sea ice evolution [*Tietsche et al*., 2014; *Blanchard-Wrigglesworth et al*., 2011].

Century-scale projections of sea ice are largely coordinated through the Comparison Model Intercomparison Project (CMIP), which contributes model projections for the Intergovernmental Panel on Climate Change (IPCC) assessment reports. The sea ice components of the IPCC AR4 and Fifth Assessment Report (AR5) CMIP models [*Vavrus et al*., 2012; *Jahn et al*., 2012] all indicate a declining trend in Arctic sea ice extent over the coming century for the business-as-usual scenarios [*Intergovernmental Panel on Climate Change*, 2007, 2013]. The projections vary widely depending on the model physics, forcings, and especially the initial sea ice extent. However, the models all were found to be underestimating the observed trend in September sea ice extent in both the AR4 models [*Stroeve et al*., 2007] and the AR5 models [*Stroeve et al*., 2012], though the AR5 models better match the historical observations. This underestimation has continued and if anything has become more pronounced in the subsequent years (Figure 7). This divergence in the trend of the model estimates and observations is a due to a combination of natural variability in the climate system and external forcing. *Wang and Overland* [2009, 2012] found better agreement when selecting a subset of models that best matched the seasonal and interannual variability in the observed record. In terms of practical applications of predictions, it is important to assess regional aspects of the changing ice cover. *Rogers et al*. [2013] evaluated several of the AR4 models and found that model performance relative to the observed historical record varied depending the sector analyzed, suggesting that selection of models should be targeted for the region of interest. It also points the way toward possible enhancements to improve models throughout the Arctic.

In addition to sea ice extent, other aspects of the sea ice system have also been compared between models and observations. Using two coupled ice-ocean models, *Adams et al*. [2011] found that polynya formation is not well simulated in the models unless landfast ice is explicitly prescribed in the models. Landfast ice extent and location are important because polynyas often form on the lee side of the fast ice as drifting ice is advected away. Polynyas are locations of high biotic productivity because they provide access between the ocean and the atmosphere. Biological impacts of the changing ice cover are discussed further in section 3.

Sea ice thickness estimates from six of the IPCC AR4 models were compared with a variety of in situ, airborne, and satellite ice thickness observations [*Johnson et al*., 2012]. As with sea ice extent and motion, significant differences were found between the model simulations and the observations with the models overestimating the thickness of thin ice, but underestimating the thickness of ice $>$ ~2 m thick; the rate of early autumn ice growth also was underestimated. Comparison of observations with the CMIP5 models in AR5 show reasonable overall agreement in mean thickness, but many models' spatial distribution of thickness within the Arctic are not representative of the observations [*Stroeve et al*., 2014c].

In short, there are numerous uncertainties in the future response of sea ice and such projections should be taken with limited confidence. *Winton* [2011] found that models underestimate the sensitivity of the sea ice to temperatures, meaning that natural variability may be playing a significant role in the misalignment between models and the current observed trends. Model projections also show that even in a warming Arctic, there is the possibility of decadal or longer periods with decreasing extent trends [*Kay et al.*, 2011]. This further suggests extreme caution in prognostications about future sea ice change.

The *Wang and Overland* [2012, 2009] results mentioned above suggest largely ice-free conditions (defined as < 1 million km^2) by 2030 (plus or minus a decade) based on the models that matched the criteria to match the observations [*Overland and Wang*, 2013], while *Massonnet et al*. [2012] yield a somewhat later range of 2041–2060. Other studies based on modeled volume estimates have suggested that an even earlier date may be possible, though such projections are based on simple extrapolation of the volume trend [*Overland and Wang*, 2013; *Maslowski et al*., 2012]. Such discussions of specific years of summer ice-free conditions are highly speculative at this point and there are many unknowns. Nonetheless, models clearly indicate that the Arctic Ocean will become largely ice-free during the summer at some point in the future as temperatures continue to increase. Much of the uncertainty in model projections of the future state are due to uncertainties in the magnitudes of positive and negative feedbacks in the sea ice-climate system.

2.7. Tipping Points, Feedbacks, and Black Carbon in the Sea Ice System

At one time, there was much discussion that the response of sea ice to natural and forced changes was not linear and that a "tipping point" may be reached [*Lindsay and Zhang*, 2005], where the sea ice changes rapidly and irreversibly. (We note here that a more rigorous definition of tipping point is simply a highly nonlinear, but still reversible, bifurcation in the system; however, in the sea ice literature, the idea of irreversibility is typically considered as well). *Eisenman and Wettlaufer* [2009] showed how the sea ice system in a simple model could exhibit hysteresis when the thermal forcing first warms and then cools the polar regions. They show that the trajectory reaches a bifurcation point (tipping point) under extreme warming when even all of the winter ice is lost. Another modeling study using a single-column model also demonstrated that a bifurcation in the sea ice system is possible, though a smooth loss can also occur [*Abbot et al*., 2011]. In light of the extreme record low minimums of 2007 and 2012, the idea of a tipping point seems plausible and such a possibility is of considerable interest, particularly in regard to impacts on human activities, discussed in section 4. The vulnerability to a tipping point scenario depends substantially on the influence of feedbacks, both positive and negative, on the future state of sea ice cover.

The most notable positive feedback is the sea ice-albedo feedback. Snow-covered sea ice is bright, reflecting roughly 85% of the incident sunlight, while the open ocean is dark, reflecting only 7% of the incident sunlight [*Perovich and Polashenski*, 2012]. As ice and the overlying snow cover melt, its albedo decreases. This results in additional absorption of solar radiation by the ice and more melting that further decreases the albedo. This positive loop is classified as the ice-albedo feedback. Under warming climate conditions, this feedback can act on longer time scales to enhance the climatic changes. An initial warming of the climate will cause the onset of summer melt to begin earlier and the autumn freeze-up to start later. This leads to a larger area of the Arctic being covered by open water and darker sea ice surfaces for a longer period of time, resulting in greater absorption of solar energy. Observations show a 0.04 decrease of albedo between 1979 and 2011 with a resulting increase of 6.4 W m^{-2} in solar energy input into the Arctic Ocean [*Pistone et al*., 2014]. The additional heat in the ocean delays the onset of fall freeze-up, possibly resulting in thinner ice. This process acts over years to decades as a positive feedback on a larger, regional scale.

Two studies have tried to quantify the strength of the ice albedo feedback by fixing the seasonal cycle of the surface albedo in climate models and comparing the results to model runs with variable albedo under a doubling of atmospheric CO_2. *Bitz* [2008] found that the impact of the ice albedo feedback factor on ice thickness is rather small in the National Center for Atmospheric Research Community Climate System Model version 3 (CCSM3) because of the countervailing thin ice growth feedback. She estimated the feedback factor f by holding the seasonal cycle of the surface albedo of sea ice and ocean fixed while doubling CO_2. Ice albedo feedback causes sea ice to thin about 26% more compared to a model run without ice albedo feedback. A reduction of 26% corresponds to a feedback factor of only $f = 0.21 \pm 0.02$, where the error here is an estimate of uncertainty in the model. As might be expected, the feedback was strongest in the seasonal ice zones. Also using CCSM3 but fixing the albedo of all surfaces, not just the ocean, *Graverson and Wang* [2009] found that

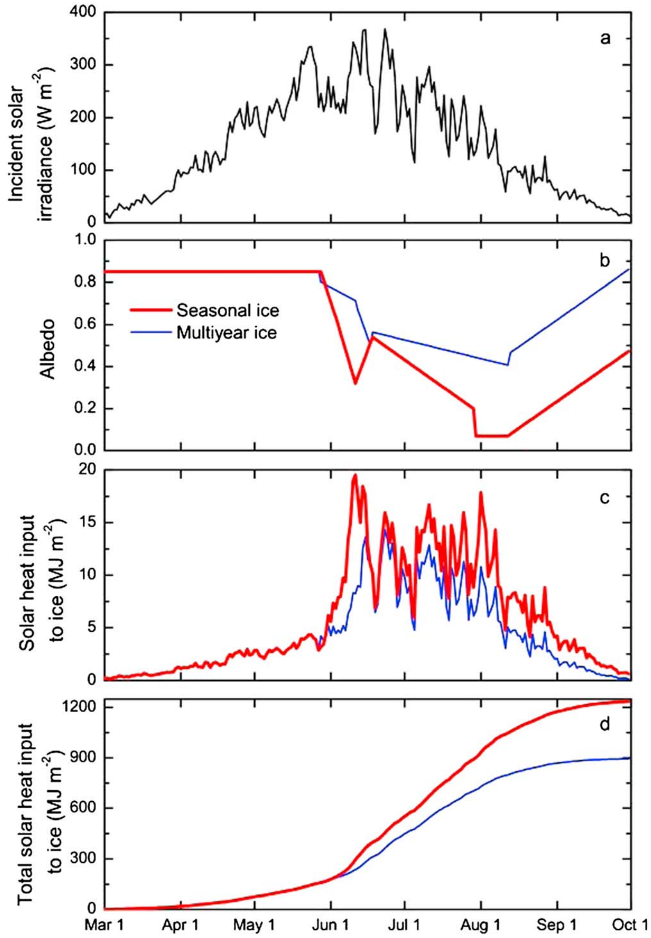

Figure 8. Time series of solar partitioning: (a) total solar irradiance observed at Surface Heat Budget of the Arctic Ocean, 1998, (b) seasonal albedo evolution for seasonal (first-year, in red) and multiyear (in blue) ice, (c) daily solar heat input, and (d) cumulative solar heat input. In Figure 8b, the albedo progression is idealized for the discrete phases of melt: (1) cold snow, (2) melting snow, (3) pond formation, (4) pond drainage, (5) pond evolution, (6) open water, and (7) freeze-up. From *Perovich and Polashenski* [2012].

the surface albedo feedback amplifies the surface-temperature response in the Arctic area by about 33%, whereas the corresponding value for the global-mean surface temperature is about 15%. Even though the surface albedo feedback is an important process underlying excessive warming at high latitudes, the Arctic amplification is only 15% larger than in the locked-albedo experiments. They found that an increase of water vapor and total cloud cover lead to a greenhouse effect that is larger in the Arctic than at lower latitudes and may explain part of the Arctic surface-air-temperature amplification.

Another study investigated the implications of the transition from a sea ice cover composed primarily of multiyear ice to one dominated by first-year ice [*Perovich and Polashenski*, 2012]. They found that while melt onset occurs simultaneously in both categories of ice, albedo declines more rapidly in first-year ice and reaches lower levels due to differences in melt pond formation and evolution on the two ice types (Figure 8). The reduced albedo results in more than 300 MJ m^{-2} of cumulative total solar heat input into first-year ice than multiyear ice over the summer. With the increasing percentage of first-year ice cover, this represents an important source of energy input, particularly since much of the Arctic Ocean is still ice covered at the summer solstice when incident solar irradiance is at its maximum.

Another important feedback mechanism for Arctic sea ice is the cloud-radiation feedback. Clouds play a dominant role in determining shortwave and longwave radiative transfer in the atmosphere. Cloud area, height, thermodynamic phase, thickness, and water content all influence radiative fluxes [*Curry and Ebert*, 1990]. As a result, there are strong couplings between the sea ice, surface albedo, and clouds, termed the cloud-radiation feedback [e.g., *Makshtas et al*., 2007].

Over the course of a year, the net effect of clouds over the central Arctic Ocean is to warm the surface [e.g., *Schweiger and Key*, 1992]. Only for a brief period in summer does the cloud cooling effect overwhelm the warming effect. This time frame is determined largely by the cloud type, Sun angle, and surface albedo. Observations over the past decade have revealed that liquid water clouds impart the greatest radiative influence on the Arctic surface radiation budget. In general, low-level stratiform liquid and mixed-phase clouds exert the most significant cloud effect on the surface radiation budget [*Tjernström and Graversen*, 2009; *Cesana et al*., 2012]. There is some evidence that low-level, thin, liquid water clouds played a key role in the extended surface melting of the central Greenland ice sheet in July 2012 [*Bennartz et al*., 2013].

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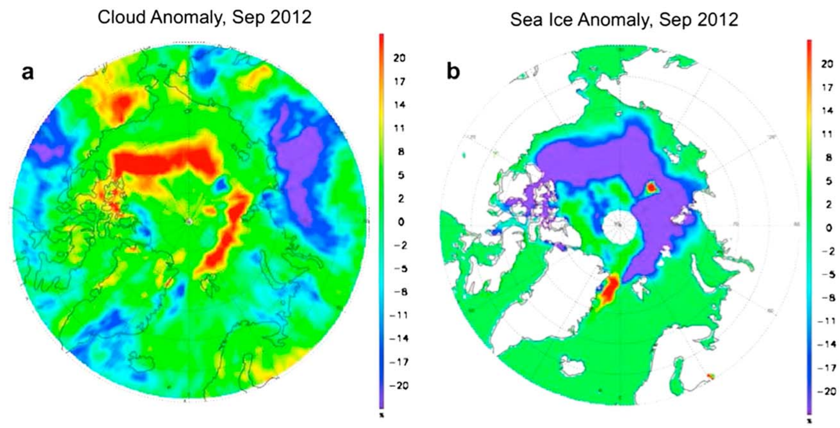

Figure 9. (a) Cloud cover and (b) sea ice concentration anomalies (in %) in September 2012 relative to the corresponding monthly means for the period 2002–2010. Data are from the Moderate Resolution Imaging Spectroradiometer on the Aqua satellite.

While the degree to which clouds influence the surface energy budget is not entirely clear, there is nevertheless a strong correlation between sea ice and cloud cover anomalies [*Overland et al*., 2012]. Positive cloud cover anomalies (more cloud) over the Arctic Ocean correspond to negative sea ice concentration anomalies (less ice). For 2012, this was particularly evident in the winter months in the Barents and Kara seas region, and in the summer months from the East Siberian Sea to the Beaufort Sea (Figure 9).

The lagged effect of clouds on sea ice must also be considered. For example, in September 2012, Arctic sea ice cover reached a record minimum for the satellite era. In the following winter, the sea ice quickly returned, carrying through to the summer when ice extent was 48% greater than the same time in 2012. *Liu and Key* [2014] showed that another factor, below average cloud cover in January–February 2013, resulted in a more strongly negative surface radiation budget, cooling the surface and allowing for greater ice growth. The areas of significant ice growth estimated from the negative cloud cover anomaly were tracked from winter to summer and were shown to correspond well with the September ice concentration anomaly pattern.

While less wintertime cloud cover can result in more summertime ice, *Kapsch et al*. [2013] demonstrate that an enhanced greenhouse effect associated with increases in clouds and water vapor in spring corresponds well to below normal end-of-summer sea ice extents. In such cases, the downward longwave radiation at the surface is larger than usual in spring, which enhances the ice melt. In addition, the increase of clouds causes an increase of the reflection of incoming solar radiation leading to the counter-intuitive effect that years with below average sea ice in September corresponded to below average downwelling shortwave radiation at the surface. Similarly, *Nussbaumer and Pinker* [2012] found that areas showing the largest accumulation of downwelling surface shortwave radiation (total shortwave radiant exposure from the beginning of the year through June) did not correspond to negative sea ice concentration anomalies.

The influence of trends in sea ice concentration and cloud cover on surface temperature over the Arctic Ocean from 1982 to 2004 was investigated analytically, and evaluated empirically with satellite products by *Liu et al*. [2009]. It was found that multidecadal changes in ice concentration and cloud cover played major roles in the magnitude of recent Arctic surface temperature trends. In winter, surface temperature trends associated with changes in cloud cover were found to be negative over most of the Arctic Ocean, with cloud cover trends explaining 0.91 out of 1.2 K decade^{-1} of the surface temperature cooling. In spring, 0.55 K decade^{-1} of the total 1.0 K decade^{-1} warming can be attributed to the trend associated with cloud cover changes. *Liu et al*. [2012] found that a 1% decrease in sea ice concentration leads to a 0.36–0.47% increase in cloud cover and that 22–34% of the variance in cloud cover can be explained by changes in sea ice.

The relationship between winds, radiative forcing, heat advection, and the dramatic decrease in sea ice cover over the past three decades has recently been examined with satellite data. *Francis et al*. [2005] found that there are distinct regional differences in the relative roles of these parameters in explaining the variability of the ice edge position. The downwelling longwave flux anomalies explained about 40% of the variability, with northward wind anomalies important north of Siberia. Anomalies in solar insolation were negatively correlated with ice retreat in all regions, so the solar flux anomalies are overwhelmed by the longwave influence. *Chen et al*. [2011] studied the role of downwelling longwave radiation in both surface temperature-water vapor and cloud-radiation feedbacks. They found that the feedbacks are strongest in the nonsummer seasons, leading to the largest amplification in surface temperature at those times. Their model results showed that later in the 21st century, however, the longwave flux becomes less sensitive to changes in water vapor and cloud thickness. Such a regime shift in sensitivity could slow the pace of Arctic change.

While the sea ice-albedo and cloud-radiation feedbacks will amplify initial perturbations, there are also important negative feedbacks that dampen any perturbations. Understanding the role of these negative feedbacks and their interaction with other aspects of system change is critical if we are to accurately model and project the future state of the Arctic. The conduction of heat through sea ice is dependent on ice thickness causing thin ice to grow more rapidly than thick ice subject to the same atmospheric and ocean forcing. This relationship is nonlinear, having an inverse dependence on the ice thickness and giving rise to a stabilizing feedback on ice thickness—more thin ice and open water at the end of summer results in faster ice growth. Indeed, a number of climate models simulate increased ice growth in future climate projections that partially compensates increases in ice melt [*Holland et al*., 2008].

There are also indications that sea ice dynamic processes may stabilize the Arctic sea ice cover. In uncoupled sea ice modeling studies, ice dynamics generally reduces the sensitivity of the ice cover to forcing perturbations [e.g., *Arbetter et al*., 1999; *Hibler*, 1980]. This is related to the ice strength-ice thickness relationship, which causes thinner ice to more easily converge resulting in more ridging and mechanical thickening of the ice pack. This can also modify the ice velocity field and observational evidence does indicate an increase in ice speed associated with the thinning ice pack [*Rampal et al*., 2009, 2011], this can have a positive feedback effect as well through faster advection of ice out of the Arctic and more open water area during the summer. Coupled model simulations [*Hewitt et al*., 2001; *Vavrus and Harrison*, 2003] have found that ice dynamics reduces the climate sensitivity to increased CO_2. However, the mechanisms responsible for this vary in different models.

Surface albedo, solar insolation at the surface, and clouds are also affected by black carbon in the atmosphere and deposited on the snow and sea ice. There has been uncertainty in the net effect of black carbon due to the competing influence of albedo depression by surface deposition and reduced insolation from suspension in the atmosphere. The surface effect enhances the ice-albedo positive feedback while cooling from the atmosphere represents a negative feedback. A recent model study [*Flanner*, 2013] indicates that, as expected, surface deposition results in a positive forcing, but black carbon in the lower and midtroposphere also leads to more warming because of changes in cloud cover. Black carbon at higher levels has a cooling effect due to reduced solar insolation. Overall, the net effect of black carbon appears to be warming, suggesting a potential mitigation strategy to slow the decline in sea ice cover [*Shindell et al*., 2012].

Recent model results have found that, because of negative feedbacks and the potential large role of natural variability in the accelerated summer extent decline of the past decade, a tipping point for Arctic sea ice now appears unlikely. In a study where all sea ice was removed from a model during one summer, in just a few years, summer ice cover recovered back to the trend line of the long-term forcing response [*Tietsche et al*., 2011], which suggests a long-term linear response with no tipping point. Other studies [*Ridley et al*., 2012; *Armour et al*., 2011] found that after the Arctic became ice-free during summer under increasing CO_2 forcing, when forcing was subsequently decreased, the ice cover returned to its previous state and that at any CO_2 level, sea ice extent would stabilize at a level in equilibrium with the CO_2 forcing and that if CO_2 were reduced, the sea ice would recover [*Amstrup et al*., 2010].

These results imply that if the climate was to become colder, the loss of sea ice that occurred during the last decades can probably be reversed. If, however, the climate continues to warm, the loss of sea ice is likely to continue. This is caused by the thinner and thinner sea ice cover becoming more and more vulnerable to ice loss during summer: With a thinner sea ice cover, a given amount of summer energy input will cause a larger fraction of the ocean to become completely ice free [*Holland et al*., 2006]. Nonetheless, the research suggests that while there may be extreme years or even several years of rapid summer ice loss, overall the sea ice currently appears to respond roughly linearly with temperature [*Armour et al*., 2011] and extreme years are largely due to natural variability, though Arctic sea ice will respond more strongly to natural forcing as it thins. This interplay between the thinner ice cover, winter ice growth, in concert with natural variability will likely lead to a less predictable Arctic sea ice cover, complicating efforts at improving seasonal and decadal predictions of sea ice [*Goosse et al*., 2009].

2.8. Successes and Remaining Challenges in Understanding the Physical State of Sea Ice

It is clear that Arctic sea ice is fundamentally changing—extent is decreasing, ice is thinning, multiyear ice is covering less of the Arctic Ocean, melt is occurring earlier, albedo is decreasing, and the Arctic is absorbing more energy due to this sea ice decline. Advances in observational capabilities, such as satellite altimetry, have greatly increased knowledge of the changes in sea ice. Sea ice models continue to improve. However, significant challenges remain. While satellite altimeters are yielding substantial data, there are still potentially large uncertainties due in part to limited knowledge of snow cover and ice density. Despite their importance, both in terms of their impact on satellite measurement uncertainty and their role in the physical evolution of the ice cover, snow observations represent a significant gap in Arctic sea ice data collection. It is crucial to address this gap to reduce uncertainties in satellite estimates and further our understanding of physical processes.

Sea ice models are improving, but general circulation models used in the CMIP projections still lack key physics, which is a significant factor in the underestimation of historical changes in sea ice extent, thickness, and motion. Further model improvements are needed to narrow uncertainties in century-scale projections. Though the current modeling results argue against the possibility of a tipping point in summer sea ice, there is still a spread of several decades in estimates of the timing of summer ice-free conditions. Such a large envelope of uncertainty complicates the development of adaptation strategies. Decadal and seasonal predictions are even more challenging due to strong interannual variability in the sea ice system. While progress is being made in terms of coordination of efforts, collection and dissemination of relevant data for initialization, and validation, Arctic sea ice forecasting is still in its infancy.

Addressing the gaps in our understanding of sea ice processes and in forecasting the future state of the ice cover (on all timescales) is crucial because the changes in the physical sea ice system cascade down through the region's ecosystem and the humans living and working in the Arctic. These two impacts are the subject of the next two sections.

3. Biological Impacts of the Changing Sea Ice Cover

3.1. Impacts on Lower Trophic Organisms and Geochemical Cycles

The Arctic sea ice system, comprised of seasonal ice cover that melts during summer and a "permanent" multiyear ice cap that typically covers much of the Arctic Ocean, is a unique habitat type which has become home to a host of Arctic species, ranging in size from viruses and bacteria, typical ice-algal species (e.g., *Nitzschia frigida*) to the charismatic megafauna such as polar bears (*Ursus maritimus*). Sea ice influences biochemical cycles through its role on radiative, fluid, and gas exchanges at the sea ice-atmosphere interface and in supporting active biological and chemical processes within the ice (see review by *Vancoppenolle et al*. [2013]). The unprecedented decline in Arctic sea ice cover extent has major impacts on species that use the ice as a habitat or depend on its presence during their life cycle (see below). But, perhaps more importantly, the changes in the duration and extent of the ice cover in the Arctic impact biochemical processes fundamental to the cycling of carbon and other elements in Arctic marine ecosystems, and energy transfers in the marine food chain. There is mounting evidence, over the past decade, of far-ranging changes in Arctic Ocean physical (e.g., deepening of the halocline and increased stratification [*McLaughlin and Carmack*, 2010]), chemical [e.g., *Mathis*, 2011], and biological processes [e.g., *Tremblay et al*., 2011; *Arrigo et al*., 2012], with important repercussions for trophic interactions and marine food webs. Changes in marine food webs have been documented at geological [*Darby et al*., 2006] and recent [*Weslawski et al*., 2000] time scales. However, currently dramatic and rapid changes in marine ecosystem structure and function are taking place, associated with sea ice decline, northern range extensions of marine species as ice-free areas open up, and changes in water column properties (warming and freshening), as discussed below.

Ice-associated food webs in the Arctic are based largely upon high and localized primary production taking place, based on recent knowledge, mostly at the ice-water interface along receding ice edges. However, mounting evidence of under-ice phytoplankton blooms [*Fortier et al*., 2002; *Mundy et al*., 2009], which can be highly productive [*Arrigo et al*., 2012] challenges this classic view and warrants critical re-evaluation of Arctic primary production estimates. Photosynthetic production in the Arctic is constrained by the annual radiative cycle, which depends on latitude, being limited by light in winter and early spring. Under the ice-cover, shade-adapted ice algae start to grow as soon as light limitation is lifted, which is associated with the spring increase in radiation when there is sufficient radiative transfer through the snow and ice matrix to generate adequate light conditions for ice algal development. The presence of snow/ice, black carbon at the snow surface, and organic (e.g., ice algae, protists, and dissolved organic matter) and inorganic (e.g., sediments) inclusions within the ice plays a fundamental role in the transmission of light to the water column and the potential development of pelagic phytoplankton communities.

Changes in the duration of the sea ice cover season, i.e., advanced melt and delayed ice formation have major impacts on the phenology of biochemical processes by impacting the periods of ice algal and phytoplankton production through: (1) earlier melt and release of ice algae and other ice-associated material into the water column, therefore shortening the period of ice algal production as it is constrained in its onset by the spring increase in solar radiation [*Wassmann and Reigstad*, 2011; *Kovacs and Michel*, 2011; *Leu et al*., 2011; *Falk-Petersen et al*., 2007], (2) an associated advance in the timing of phytoplankton growth including the development of under-ice blooms, as discussed in more detail below, causing (3) potential shifts in the contribution of ice algae and phytoplankton to marine food web transfers. Delayed ice formation and increased storm surges during fall may also impact the preconditioning of water column properties which can in turn influence ice-associated production the next spring. More frequent wind-driven coastal upwelling could induce higher surface nutrient concentrations which are unlikely to be depleted by phytoplankton during short sunlit days in fall and may therefore be available for spring production. Late ice formation and the increase of winter polynyas and open leads in the ice may also influence processes of incorporation of protist cells in the forming ice matrix, with potential impacts on the biomass and composition of spring ice algal communities [*Riedel et al*., 2007; *Niemi et al*., 2011].

Extended open water periods could potentially allow for the development of a second phytoplankton bloom fuelled by nutrient replenishment through vertical mixing in the fall. Such a seasonal pattern is observed in the Canadian Arctic Archipelago and the North Water Polynya [*Ardyna et al*., 2011; *Caron et al*., 2004] and is similar to boreal regions. However, since nutrient inventories and the nutrient supply to surface phytoplankton ultimately determine the maximum phytoplankton yield and the biomass available to the food web, a combination of factors (not solely the duration of the open water period) will interact to determine the extent and locations of increased phytoplankton production (see section 3.2 below).

Primary production in the water column depends, in broad terms, on a balance between stratification and mixing, the former keeping phytoplankton cells within the surface layer where enough irradiance is available for photosynthesis, and the latter fuelling the supply of new nutrients to support production. In the context of current Arctic change, factors that increase light transmission to the water column will favor the onset of the phytoplankton bloom. Early snow/ice melt and the release of particulate and dissolved substances from the sea ice increase under-ice light availability, supporting phytoplankton photosynthesis. In addition, the presence, areal, and geometric distribution of melt ponds during the melt season creates complex under-ice light conditions [*Frey et al*., 2011]. In the central Arctic Ocean, changes in sea ice including decreasing ice thickness, multiyear ice and ridges, likely increased light transmission to surface waters over the past years [*Wang et al*., 2014], impacting primary production [*Nicolaus et al*., 2012]. A new habitat for ice communities, in so-called “melt holes” has recently been observed in the central Arctic Ocean [*Lee et al*., 2012]. The melt holes are directly connected to the seawater and contain abundant sea ice algae, mainly the diatom *Melosira arctica*, which is known to form long mats at the under-ice surface. Recent evidence of widespread deposition of *M. arctica* in the central Arctic Basins reveals the importance of this ice-associated species for Arctic primary production and carbon cycling [*Boetius et al*., 2013].

There is evidence that early melt can trigger the development of under-ice phytoplankton blooms, as shown in the Canadian Archipelago [*Fortier et al*., 2002]. Under-ice phytoplankton blooms are reported in earlier literature, for example, in Hudson Bay [*Michel et al*., 1993]. More recent evidence of under-ice phytoplankton blooms in the Beaufort Sea [*Mundy et al*., 2009; *Forest et al*., 2011] and the Chukchi Sea [*Arrigo et al*., 2012] suggests that they are widespread in the Arctic. The regularity of occurrence, extent, and contribution to overall ecosystem production of under-ice blooms is currently unknown. These blooms, not detected by

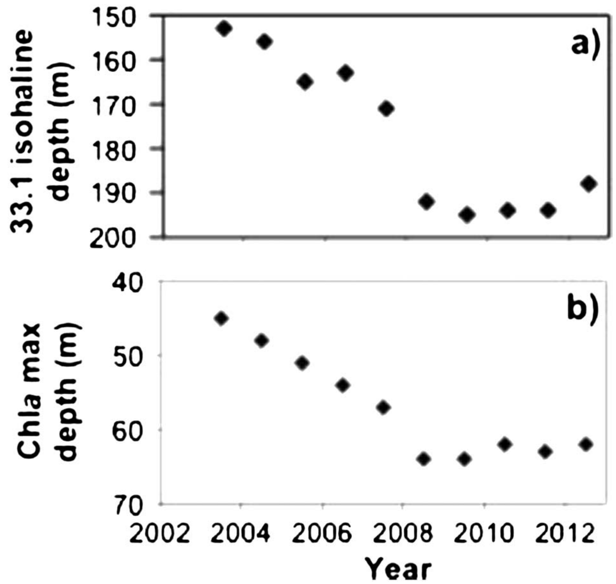

Figure 10. Secular time series of mean near-surface properties of the Beaufort Gyre region of the Canada Basin as measured in August and September by the Joint Ocean Ice Studies (*CCGS Louis S. St-Laurent*) in collaboration with the Beaufort Gyre Exploration Project of the Woods Hole Oceanographic Institution. Each data point is the mean of that property for a set of stations that are repeated each year in the southern Canada Basin and representative of the Beaufort Gyre (following *McLaughlin and Carmack* [2010]). (a) Depth of the 33.1 practical salinity unit isohaline and (b) depth of the subsurface chlorophyll maximum. Adapted from *Frey et al.* [2012].

remote sensing techniques, are not accounted for in recent estimates of Arctic primary production and secular trends [*Arrigo et al*., 2008; *Arrigo and van Dijken*, 2011].

In the absence of light limitation, nitrogen-based nutrient supply is considered to be a key factor for sustaining primary production in the ice and the water column [*Rózanska et al*., 2009; *Tremblay and Gagnon*, 2009]. Mixing and upwelling of nutrient-rich waters and changes in water mass distribution driven by large-scale atmospheric forcing can contribute to the variability in nutrient supply and primary production in surface waters [*Michel et al*., 2006; *Williams and Carmack*, 2008; *Apollonio and Matrai*, 2011]. The widespread occurrence, in the Canadian Arctic, of deep chlorophyll *a* (chl *a*) maxima localized near the nutricline reflects the interplay of factors affecting surface stratification and nutrient supply on phytoplankton development [*Martin et al*., 2010, 2013]. In the Canada Basin, a deepening of the deep chl *a* maxima over the past decade is linked to freshening and an increase in surface stratification (Figure 10) [*McLaughlin and Carmack*, 2010; *Morison et al*., 2012]. The strengthening of stratification also impacted the size structure of phytoplankton communities, with increasing abundances of small cells and associated impacts on food web linkages [*Li et al*., 2009]. In concert with these changes, increased bacterial activity and respiration in a warmer stratified surface layer imply that the Arctic Ocean may not become a larger sink for CO_2 under future climate scenarios [*Kirchman et al*., 2009; *Cai et al*., 2010].

Some of the impacts of the decrease in sea ice extent, which affects the fall period mainly, are similar to those described above for spring. An increase in open water areas in summer/fall extends the areas available for potential wind-driven mixing and upwelling, whereas ice melt strengthens surface stratification. Of key importance is the location of the new open water areas, as additional surface radiation in the surface layer will not increase annual production in nutrient-limited systems. Regional differences in phytoplankton regimes and in their responses to sea ice changes emphasizes that there is not a unique response of Arctic ecosystem to ongoing changes [*Ardyna et al*., 2011]. Increases in production are associated with wind-driven upwelling at the shelf break and at the ice edge in the coastal regions [*Mundy et al*., 2009; *Tremblay et al*., 2011] in contrast to central basins where stratification prevails [*Li et al*., 2009].

Superimposed on sea ice associated changes in light conditions, stratification and mixing, timing of ice formation/melt, and position of ice edges, other major changes such as increased riverine input, increased sea surface temperature, increased air temperatures, melting and receding glaciers, changes in precipitation and atmospheric forcings are also taking place in the Arctic and contributing to the modification of marine ecosystems. Higher freshwater inputs from sea ice melt and terrestrial runoff, together with warming of the surface layer, increase surface stratification. This might offset the potential for increased nutrient supply from deep waters to the surface layer due to increased storms and wind mixing in open water areas. On the shelves, allochthonous input of nutrients and denitrification also contribute to nutrient inventories and fluxes to primary producers. Additional factors such as increased transport and resuspension of dissolved and particulate material, including sediments, also modify the quantity and spectral quality of light available to primary producers on shallow shelves. Carbonate and aragonite undersaturation is prevalent in freshwater-influenced areas, from the Chukchi Sea to the eastern Canadian archipelago [*Bates et al*., 2009; *Chierici and Fransson*, 2009; *Azetsu-Scott et al*., 2010] and in the eastern Bering Sea where areas of seasonal $CaCO_3$ mineral suppression prevail [*Mathis*, 2011].

Increasingly, it is apparent that multiple combined effects of physical, chemical, and biological changes are taking place, challenging our capacity to predict directional changes in Arctic marine ecosystems. For example, increases in phytoplankton production can amplify the effects of ocean acidification by increasing pCO_2 and decreasing pH in waters that become more corrosive to $CaCO_3$ [*Mathis*, 2011].

Recent studies based on fatty acid markers have provided evidence for the critical role of lipid-rich ice algae in the development and survival of key zooplankton species in Arctic marine food webs [e.g., *Søreide et al*., 2010]. The timing of ice melt and retreat is a key structuring element for Arctic marine food webs and for the reproductive success of marine birds and mammals. Ice edges [*Perrette et al*., 2011] and polynyas typically represent areas of high productivity that provide spatially and temporally predictable regions where large numbers of marine birds and mammals congregate to feed [*Kovacs and Lydersen*, 2008; *Kovacs et al*., 2011].

The biological impacts associated with the shift from multiyear to seasonal ice are complex and will be derived from the strong modifications in physical forcings associated with multiyear ice melt (e.g., increase in freshwater content and stratification, and increase in light availability) together with direct impacts associated with the loss of permanent sea ice. Arctic food chains may become more similar to those in the Antarctic where seasonal ice makes up over 80% of the sea ice. Loss of multiyear ice in the central basins and displacement of the fast-ice and marginal ice zone relative to the shelf slope break where wind-forced upwelling occurs, are likely to induce ecosystem responses. In addition, as the ice edge retreats northward, the delineation between Arctic and boreal communities will likely also retreat to the north resulting in range expansions of temperate species, and contractions of Arctic species, as documented during previous warm periods and in recent years [*Berge et al*., 2005; *Beuchel and Gulliksen*, 2008; *Beaugrand et al*., 2009; *Gilg et al*., 2012].

Zooplankton and fish species that feed in association with sea ice, or shelter within its interstitial spaces are expected to be impacted negatively by the loss of multiyear sea ice (MYI) and the shortening of the sea ice season in Arctic waters [e.g., *Søreide et al*., 2008; *Leu et al*., 2011]. Changes in the calanoid copepod community have already been documented in the Barents Sea region, with temperate species being found increasingly farther north, to the likely detriment of endemic Arctic species [*Søreide et al*., 2010]. Subpolar species are unlikely to be able to migrate into the Arctic, even under warming conditions, because of a mismatch in timing of food availability [*Ji et al*., 2012]. Fish, seabirds, seals, and even some cetaceans (i.e., bowhead whales, *Balaena mysticetus*) rely heavily on the lipid-rich Arctic copepods and amphipod species (e.g., *Parathemisto libellula* and *Themisto abyssorum*) to build their own lipid stores [e.g., *Karnovsky et al*., 2003], so changes in key lower trophic species will have impacts throughout Arctic food webs. Arctic cod (*Boreogadus saida*) and polar cod (*Arctogadus glacialis*), two small, ice-associated fish taxa, are critically important prey of many Arctic seabirds and sea mammals [*Bluhm and Gradinger*, 2008]. Changes to these two species alone will have impacts through to the top of the Arctic food web.

3.2. Top Trophic Species Response to Changing Sea Ice

The rapid changes in the Arctic sea ice cover are increasing the vulnerability of ice-dependent upper-trophic arctic animals [e.g., *Tynan and DeMaster*, 1998; *Simmonds and Isaac*, 2007; *Laidre et al*., 2008; *Kovacs and Lydersen*, 2008]. Sea ice declines are recognized as a major threat to many endemic marine mammals in the Arctic [e.g., *Kaschner et al*., 2011; *Kovacs and Michel*, 2011]. Declines in their breeding, molting, and resting ice habitats will be exacerbated by the declining sea ice conditions providing new habitats to migrant whales and boreal seals and cetacean species that have previously been limited in their distributional extent by sea ice cover [see *Gilg et al*., 2012]. These range extensions will likely result in increased competition for food between these temperate species and the endemic marine mammals and increased the risk of disease [*Kovacs et al*., 2011]. The impact of changing ice conditions on seabirds are expected to be controlled principally through changes in food availability due to changes in ice edge location that have in the past provided concentrated resources close to colonies [*Kovacs et al*., 2012]. Despite limited monitoring and the difficulties of maintaining time series on long-lived animals in isolated, logistically challenging arctic environments, data are accumulating indicating that significant changes have already taken place among top trophic animal populations in the Arctic in terms of diet, behavior, distribution, and demographics.

Some seabird populations have experienced dramatic declines that are concomitant with regional declines in sea ice. Ivory gulls (*Pagophila eburnean*) are perhaps the most dramatic example, where some populations have declined by 80% during the last two decades [*Gilg et al*., 2009; *Gaston et al*., 2012a]. But others species such as spectacled eiders (*Somateria fischeri*) in the Bering Sea have also declined markedly, in parallel with declines in their dominant clam prey populations, which are thought to be suffering from reduced nutrient supplies to the benthic environment due to reduced seasonal ice cover [*Lovvorn et al*., 2009]. Dietary shifts away from traditional arctic fish species (e.g., polar cod or arctic cod) toward subarctic fish species have been documented in thick-billed murres (*Uria lomvia*), accompanied by demographic shifts that are thought to be driven by changes in the length of the ice-free season [*Gaston et al*., 2012b; *Provencher et al*., 2012]. Ongoing declines in the rate of energy delivery to nestlings in this same species, linked to reductions in sea ice coverage in their wintering range, are possibly approaching critical levels [*Smith and Gaston*, 2012]. On regional scales, polar bear (*U. maritimus*) predation on ground nesting arctic birds is becoming an issue because the bears are not able to access their normal seal prey on the fast ice; they get stranded on shore by early ice breakup and eat whatever they can find [*Smith et al*., 2010; *Rockwell et al*., 2011].

Polar bears have switched their denning habitat from multiyear sea ice to land and are being seen more regularly on beaches in Alaska [*Fischbach et al*., 2007]. This latter phenomenon of spending more time on shore is being seen in many arctic areas, as sea ice recedes earlier and forms later, leaving bears stranded on shore for longer periods [*Schliebe et al*., 2008; *Gleason and Rode*, 2009; *Towns et al*., 2010]. Less sea ice in the Barents Sea region has resulted in bears shifting denning northward because traditionally favored denning areas in the south of the Svalbard Archipelago at Hopen Island are no longer connected by ice in the fall [*Derocher et al*., 2011]. Declining sea ice conditions are also thought to be the cause of bears spending more time engaged in long-distance swimming in some regions, putting cubs at risk [*Pagano et al*., 2012]. Less land-fast ice in fjord regions is also reducing vital spring hunting habitats for females with young cubs [*Freitas et al*., 2012]. Ice in key polar bear habitats in the Canadian Arctic is increasingly fragmented, which will affect movement of polar bears [*Sahanatien and Derocher*, 2012]. Declines in sea ice to date have been linked to reduction in body condition, decreased cub survival, decreased breeding rates, and in the southern parts of the range decreased abundances of polar bears [e.g., *Regehr et al*., 2007, 2010; *Rode et al*., 2012]. If sea ice continues to decline, the range of polar bears will be markedly reduced, and their long-term viability as a species may be uncertain [*Durner et al*., 2009; *Hunter et al*., 2010; *Stirling and Derocher*, 2012].

Other marine mammals are generally less well studied than polar bears, but impacts of changing ice conditions have also been documented in the past decades for various ice-dependent pinnipeds. For example, Pacific walruses (*Odobenus rosmarus*) have shifted their summer distribution and haul-out patterns markedly, coming ashore in vast herds on the coasts of Alaska and far eastern Siberia as the Bering Sea ice has retracted north of the shelf in recent years, increasing the risk of calf mortality [*Udevitz et al*., 2013]. Availability of suitable ice has become an issue for harp seals (*Pagophilus groenlandicus*) at their southernmost breeding area and breeding failure occurs more frequently now than a few decades ago [e.g., *Bajzak et al*., 2011; *Johnston et al*., 2012], and a recent dramatic reduction in pup production of this species has been documented in the White Sea population [*International Council for the Exploration of the Sea*, 2013]. Additionally, unprecedented high numbers of harps seals have been found concentrated along central west Greenland in recent years in winter, suggesting that births might be occurring in new areas [*Rosing-Asvid*, 2008]; large herds have also been seen unexpectedly far north, in Svalbard, in late winter [*Kovacs et al*., 2011]. Another pack-ice breeder in the North Atlantic, the hooded seal (*Cystophora cristata*), has declined in abundance by more than 80% in the Northeast Atlantic, at least in part due to breeding habitat deterioration [*Salberg et al*., 2008; *Øigård et al*., 2014], and a delay in the mean age of first pregnancy, and reduced pregnancy rates have been documented for the Northwest Atlantic population of hooded seals that are thought to be based on ecosystems change [*Frie et al*., 2012]. Ringed seals (*Pusa hispida*) and bearded seal (*Erignatus barbatus*) breeding habitat has also declined markedly in some regions within the Arctic and body condition and breeding success of ringed seals have been shown to be negatively impacted by ice extremes [e.g., *Harwood et al*., 2012]. Similar to the change in diet documented for some seabirds in the Canadian Arctic, harbor seals (*Phoca vitulina*) in Svalbard have shifted their fall diet from a dominance of polar cod (*B. saida*) to a dominance of Atlantic cod (*Gadus morhua*) over a decadal period [*Colominas*, 2012].

Table 3. Results, Responses, and Direction of Effects of Sea Ice Change on Humans

Type of Sea Ice Change	Affects	Result	Response
Shorter duration of landfast ice	Landfast ice travel (locals)	Personal safety and food security compromised	Changes in transport mode, new equipment needed
Poorer ice quality	Harvesting opportunities		Change in diet
Melt of MYI	Release of legacy contaminants		
Longer/larger open water season at the coast	Wider fetch (combined with increased storminess)	Coastal erosion, harbor degradation	Shoreline stabilization, resettlement, engineering options
Longer/larger areas of ice-free ocean	Increased possibilities for shipping	More traffic, more tourism, more accidents	Improved: mapping, infrastructure, harbors, search and rescue, emergency, prevention, preparedness and response, training, and coordination of tourism
	Increased possibilities for nonrenewable resource exploitation	More disturbance, better resupply, more jobs (?)	International legal agreements
	Changes in species composition	Ballast/pollution, changes in fishing opportunities	

There is also evidence that cetaceans are also responding to declines in arctic sea ice. Killer whales (*Orcinus orca*) sightings have increased markedly in the eastern Canadian Arctic over a period of decades; associated with changing ice patterns [*Higdon et al*., 2011], blue whales (*Balaenoptera musculus*) have been acoustically recorded in Fram Strait over an extended seasonal period, covering June through until October [*Moore et al*., 2011], and North Atlantic right whales (*Eubalaena glacialis*) appear to have spread north as southeast Greenland [*Mellinger et al*., 2011]. Similarly, in the Pacific regions, fin whales (*Balaenoptera physalus*) are present in the Bering Sea almost year round now [*Stafford et al*., 2010] and gray whales (*Eschrichtius robustus*) are spending increasingly long periods in arctic waters, delaying the southward migrations [*Moore*, 2008]. White whales (*Delphinapterus leucas*) in West Greenland have shifted their summer distribution westward as sea ice has declined [*Heidi-Jørgensen et al*., 2010]. Sea surface temperature changes (intimately linked to sea ice formation) have also been implicated in changing phonologies of movements in this species in the Canadian Arctic [*Bailleaul et al*., 2012]. Bowhead whale (*B. mysticetus*) distribution has also shifted recently, with significant population level implications; Alaskan and Greenlandic populations, which have been separated by ice in the past, are now overlapping spatially in the Northwest Passage [*Heidi-Jørgensen et al*., 2012].

Some ice-dependent marine mammal populations such as some bowhead whale stocks and Chukchi polar bears are showing positive trends in terms of population growth or body condition currently in spite of regional losses of sea ice [*Givens et al*., 2013; *Rode et al*., 2014]. These local responses may be due to increased productivity creating high prey availability [e.g., *Falk-Petersen et al*., 2014], or in other cases, the changes may be due to shifts in hunting regimes, but these positive trends are likely to be temporary and a reversal is expected if sea ice conditions continue to decline in the future.

4. Sea Ice Change and Human Society

The linkages between changing sea ice and societal conditions are complex, often indirect and in many ways intangible. Increasing danger of using the sea ice is linked to increased risk-taking when the time possible for hunting, fishing, and travel is being reduced, with diminishing skills and decreasing reliance on traditional knowledge among younger generations, decreasing reliability on traditional knowledge as conditions change, and use of new harvesting technology [see also *Pearce et al*., 2010; *Taverniers*, 2010]. Likewise, the implications of changing sea ice conditions for food security are exacerbated by rising commodity prices, increasing resource harvesting costs due to changes from ice to open-ocean fishing (fuel prices and equipment) [*Hovelsrud* *et al*., 2008], and weakening food sharing networks, as confirmed by more recent studies [e.g., *Ford and Goldhar*, 2012] (Table 3).

Owing to considerable historical interannual and decadal climate variability, and colonial history and encounters, Arctic indigenous people are highly adaptable and flexible in their practices and cultural repertoire [*Hovelsrud et al*., 2011, and references therein; *Cameron*, 2012; *Crate and Nuttall*, 2009]. However, the past couple of years have seen new record sea ice lows and adaptive efforts are currently strained by the magnitude and rate of the changes. Simultaneously, the Arctic is experiencing demographic changes and the major trend in most Arctic regions is migration losses (of both indigenous and nonindigenous people with a higher percentage of young women out-migrating) to the urban and southern regions impacting household size [*Rasmussen*, 2011], and migration gains by people seeking work in resource extraction and the service sectors [*Heleniak and Bogoyavlenskiy*, 2013]. The outmigration trend is projected to continue, with traditions and resources being jeopardized both by direct climate change impacts and the increasing value of their resources for market purposes. Additionally, the gender roles are shifting with women being the wage earners in order to support the male-dominated harvesting activities [*Ford and Goldhar*, 2012]. These combined and interacting changes will require additional adaptation efforts in the Arctic.

Changes in sea ice cover and timing of freezeup and breakup are in many ways closely linked to subsequent changes in infrastructure such as transport and travel, ice pileup and ride-up, increased fetch and coastal erosion. Current observations show that reduced seasonal sea ice coverage is already leading to greater shoreline exposure to open water and storm waves. These changes cause greater wave action and erosion hazards for the shoreline, infrastructure, waterfront structures, and also cultural heritage sites. Even some ice-bound coasts with negligible past wave action will be highly susceptible in the future. Where seasonal open water has been extensive in the past, later freezeup and earlier breakup increase the probability of storm wave action, even with no change in storm activity [*Walsh et al*., 2011]. Hazards related to sea ice movement (ride-up and pileup) onshore are known to have caused fatalities and significant damage to infrastructure in the past. Changing climate will reduce the probability of multiyear shore ice pileup, but thinner ice may be more susceptible to pileup and a shortening of the ice season will therefore not decrease the probability of such occurrences.

Reduced sea ice is already allowing for increased activities such as shipping, tourism, and resource extraction. Traffic using the Northern Sea Route (NSR) ports has increased significantly along with the cargo volume over the past years (Figure 11). The NSR administration office issued 635 permissions to navigate the NSR in 2013, with 71 transits of these taking place compared to only 4 in 2010 [*Barents Observer*, 2012; *Northern Sea Route*, 2014]. Much of the current Arctic shipping is destinational, and most of the ships sail under the Russian flag, indicating that international interest is currently small in comparison [*Keil*, 2014]. While tanker traffic across the NSR has increased, data obtained from the Association of Arctic Expedition Cruise Operators indicate that the number of cruise passengers visiting two of the Arctic's main tourist hubs, Svalbard and Greenland, has been stable for the last 5–6 years, after a substantial increase of 14% per year between 2001 and 2008 [*Jørgensen–Dahl and Wergeland*, 2013] but with a significant continued growth potential [*Østereng*, 2013]. While the vessels navigating the Arctic sea routes, in particular the NSR, save time and money from the shorter distance, much of the gains is currently lost to the costs associated with paying for ice breaker support, high insurance, and investments in ice-strengthened ships for a relatively short season for the polar sea routes. The expected boom in shipping through the NSR has not materialized. This is illustrated by the 2012 cargo volume figures: 1.25 million t through the NSR compared with 740 million t through the Suez Canal. The shipping companies are apparently hedging possibly awaiting better infrastructure, lower costs, longer seasons, better port facilities, and sufficient search and rescue systems.

Increased activities have a variety of impacts on the local and global climate and environment. Recent studies have found that the black carbon contribution on snow mostly comes from petroleum activity and only very little (2.35%) comes from shipping activity [*Ødemark et al*., 2012]. The same study reports that emissions from ships have an overall cooling effect on the Arctic climate while petroleum extraction has an overall warming effect. Although there are differences in their impact on the global climate, at the local and regional level, both activities will have large consequences.

New shipping routes pass through areas currently used for subsistence or local harvesting and will likely impact the ecosystem local communities use for provisioning. An example from the Russian Arctic shows that increased shipping and tourism activities have an effect on the local exchange and consumption of local food stuffs on the

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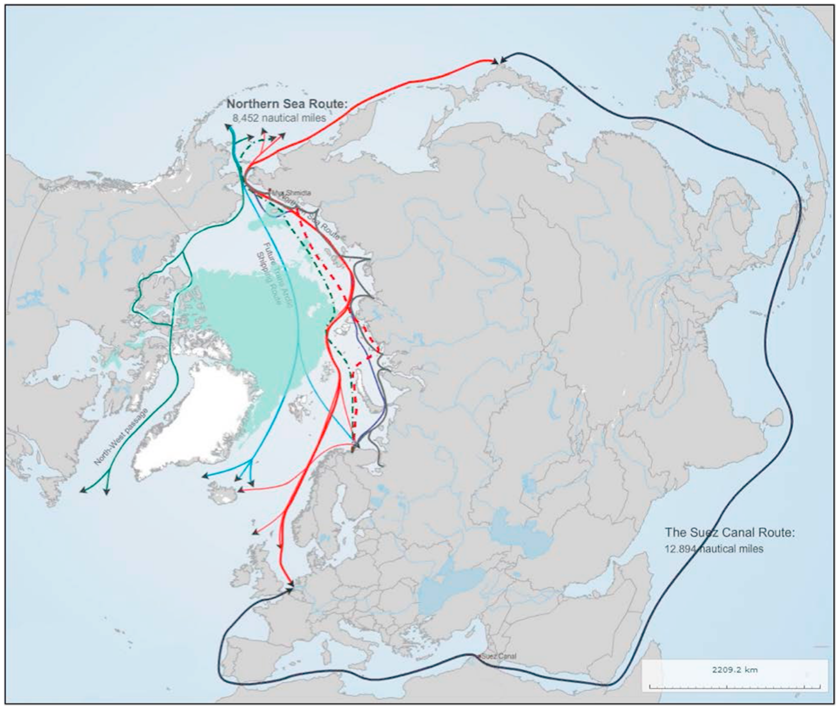

Figure 11. Current and projected Arctic shipping routes (green: North-West passage; red: Northern Sea Route; blue, Future Trans-Arctic Shipping Route; dotted and other lines along Russian coast: alternative NSR trajectories and Russian coastal route). A comparison of the length of the NSR is made with the Suez canal route, and the September 2012 minimum sea ice extent is indicated for reference (green shaded area at the pole). Figure courtesy of the Arctic Portal (www.arcticportal.org).

Vaigach Island [*Davydov and Mikhailova*, 2011]. Increased contamination and pollution affects food webs in the Arctic, and potential environmental catastrophes pose serious clean-up problems in ice-infested environments [*van Oort et al*., 2011]. Arctic species are particularly vulnerable to environmental pollution, because their limited options to find new habitat. According to statistics by the *International Tanker Owners Pollution Federation* [2013] on accidental oil spills from tankers, carriers, and barges worldwide, the incidence of large oil spills over the period 1970–2012 has decreased dramatically from 55% in the 1970s to 5% in the 2000s. Meanwhile, the same source reports that seaborne oil transport worldwide has increased steadily since the 1970s. Specific data on Arctic spills could not be obtained, but recent (January 2013) events with the Shell oil rig Kulluk running adrift and finally aground [see, e.g., *Alaska Dispatch*, 2013] illustrate that the oil industry is eager to start drilling in the Arctic Ocean. Luckily, this event took place within minutes by air from nearby search and rescue (SAR) facility, but it demonstrates that the Arctic conditions are underestimated and the pressing need for sufficient SAR capabilities and infrastructure development. Recent developments underscore this trend; many large oil companies are halting or slowing down their plans for Arctic exploration and drilling activities due to the high costs and risks, the current economic climate, and more promising investments in other regions [*Arctic Journal*, 2014a]. The withdrawal of oil companies from some northern areas such as Alaska affects local businesses who report losses in hotel revenues, restaurant businesses, and in the local marine support. Local governments may in turn see reduced fees and revenues generated by oil companies [*Bristol Bay Times*, 2014].

Another follow-on effect of a more accessible Arctic is the intensified exploration of the vast hydrocarbon and mineral deposits. In addition to affecting coastal communities and infrastructure, this will have land-inward consequences which affect local activities and land use [e.g., *Kumpulaa et al*., 2011]. Currently, Greenland is seeking to expand its mining activities and is looking into how it can legally and practically import labor from other countries. Discussions abound in Greenland about the positive effects on the economy versus the potentially negative effects on local communities and the environment, exemplifying how increased activities raise questions with respect to impacts on local communities, including their sea ice use [*Nuttall*, 2012]. This discussion has taken another turn as a recent decrease in companies' interest in Greenland's oil and gas potential may mean that it has to put its sovereignty plans on hold, although exploitation would even in the "best case scenario" not have been a guarantee for fully subsidizing such an event [*Rosing et al*., 2014]. Arctic residents' relations with changing sea ice conditions are challenged by the need to balance cultural and social norms with the need for a viable economy. People adapt by taking advantage of new technology, changing resource use patterns, and further increasing the consumption of store-bought foods. Local adaptation to sea ice change is complicated by different concerns and interests within a community, within and between sectors, or stakeholder groups, by both direct and indirect consequences of sea ice change for a local community, and by the fact that responding to sea ice change under uncertainty and across borders creates profound governance and resource management challenges [see also *Lovecraft and Eicken*, 2011; *Ford and Goldhar*, 2012]. Although there has been an increased emphasis on research, policy development, and governance to address projected effects of changing sea ice conditions, cooperation has particularly focused on how to deal with the increasing industrial activities, shipping, and infrastructure. National issues such as government spending in relocation of villages threatened by coastal erosion have not seen the same advances [*Huntington et al*., 2012].

While sea ice change represents an opportunity for some, the combination with the interaction of multiple biophysical and socioeconomic stresses are challenging for many local and indigenous peoples. The environment is changing beyond what is previously experienced, and the capacity for adapting to the combined and interactive effects of future climatic and societal change is uncertain [*Ford and Pearce*, 2010]. Studies of the Russian north corroborate the findings in the Canadian and American north on the combined effects of climate and increased activity on local people. Importantly, the study underlines that impacts of increased activity are not something of the future but are already a reality, affecting the local economy and household livelihoods [e.g., *Davydov and Mikhailova*, 2011].

4.2. Governance Progress and Challenges

Reduced sea ice, both in terms of ice conditions and season (lowest sea ice maximum since 1979 was measured in September 2012), has led to a rapidly increasing international interest and activities in the region, including from the European Union, China, Korea, and Japan; recently, the U.S. Secretary of State, John Kerry, announced that they will appoint an Arctic representative [*Eye on the Arctic*, 2014]. This has opened extensive discussions about access and rights to resources, shipping, resource extraction, military operations, and tourism [e.g., *Hovelsrud et al*., 2011; *van Oort et al*., 2011, and references therein], and most circumpolar countries are attempting to expand their claims and extending their economic zones [e.g., *Voice of Russia*, 2014]. Increased activities require increased attention from national and international resource management regimes and politicians in order to govern the impacts of an Arctic covered with less sea ice. Linking the reduction in sea ice to climate change recognizes that this is a global phenomenon and therefore beyond the jurisdiction of any Arctic state. This is exemplified by a recent meeting held in Nuuk, Greenland, where the five Arctic coastal states discussed the implications of an increasingly ice-free Arctic Ocean for fishing. Although they did not agree on a complete moratorium on commercial fishing, measures are to be taken to deter unregulated fishing while the sustainability of the ecosystem is assessed in detail, and it was agreed to promote, "scientific research and to integrate scientific knowledge with traditional and local knowledge with the aim of improving understanding of the living marine resources of the Arctic Ocean and the ecosystems in which they occur." [*Nunatsiaq Online*, 2014].

The view that Arctic governance extends beyond the Arctic states is exemplified by the recent Chinese application for permanent observer status to the Arctic Council, a high-level intergovernmental forum for cooperation, coordination, and interaction among the Arctic states. The council also involves Arctic indigenous peoples and other Arctic inhabitants in discussing Arctic issues, such as sustainable development and environmental protection in the Arctic (http://www.arctic-council.org). According to a speech by the Chinese Ambassador to Norway on 21 January 2013, China is interested in marine shipping and trade, and in contributing to peace and research in the Arctic (Ambassador Zhao Jun, Arctic Frontiers 2013, http://www.arcticfrontiers.com).

In order to meet the challenges, a multilevel governance (including international law and agreements) approach is needed. There are, however, clear limits to any Arctic governance regime whether it is regulatory or soft law, and currently, the United Nations Convention of the Law of the Sea is the only international instrument in place. There has been a general lack of preparedness, across local, national, and international levels, to respond to increased pollution and hazards (e.g., SAR needs and environmental clean-up) as sea ice decreases and access to ice-free areas increases. Successful recent attempts to rectify this have been undertaken by the Arctic Council;

on12 May 2011, the member states that Canada, Denmark, Finland, Iceland, Norway, Russia, Sweden, and the United States signed the first legally binding instrument, the Agreement on Cooperation on Aeronautical and Maritime Search and Rescue or the Arctic Search and Rescue Agreement for short. The agreement coordinates international SAR coverage and response in the Arctic and establishes the area of SAR responsibility of each state party. The Arctic Search and Rescue Agreement is the first binding agreement negotiated under the auspices of the Arctic Council. The agreement reflects the Arctic region's growing economic importance as a result of its improved accessibility due to global warming [*Arctic Council*, 2011]. The Arctic Council is in the process of a similar agreement on how to prevent, prepare for, and respond to potential pollution from oil production in the Arctic.

Talks are accelerating on binding pollution and safety rules for shipping through Arctic waters [*Globe and Mail*, 2014]. If countries keep on schedule, the Polar Code, under the International Maritime Organisation likely to come into force in 2016, is a mandatory set of standards for ships operating in the Arctic and Antarctic waters. Proponents of the code, developed over nearly two decades, point out that the legally binding guidelines will ensure that ships are designed specifically for sailing in Polar regions, as well as setting standards for crew training and safety equipment. However, the adequacy of those rules was thrown into doubt recently when Lloyd's, an insurer, announced that it planned to develop its own Arctic sailing guidelines [*Arctic Journal*, 2014b].

Recent studies continue to stress that it is important for policy makers and researchers to understand that residents of the circumpolar north remain connected with sea ice, not only through the use of sea ice but also through the role it plays for health, social activities, and cultural identity [*Downing and Cuerrier*, 2011; *Lovecraft and Eicken*, 2011; *Ford and Goldhar*, 2012]. Despite the impact of climate change on indigenous people, they are among the groups least likely to have their substantive and procedural rights recognized. As a consequence, indigenous people's rights are challenged both by climate change itself and by the current policy measures to mitigate it [*Williams*, 2011]. A point that continues to be stressed is the involvement of indigenous people in governance issues, which is not only of great importance but also an ethical obligation. It is therefore crucial to foster linkages among indigenous and traditional knowledge and scientific knowledge systems for the mutual benefit to both indigenous communities and scientific studies [*Gearheard et al*., 2010; *Huntington*, 2011; *Alexander et al*., 2011; *Downing and Cuerrier*, 2011; *Lovecraft and Eicken*, 2011; *Hovelsrud et al*., 2011].

The melting of the Arctic sea ice is removing a critical barrier which so far has prevented parasites such as *Sarcocystis*, now identified in gray seals, from moving north [*Science Now*, 2014]. A recent discovery of a 30,000 year old giant virus, appropriately named *Pithovirus sibericum*, in melting Siberian permafrost shows that old viruses may gain new life (Science News). Even though this particular virus infects only amoebae, questions arise about the resurrection of other (giant) viruses, freed by melting ice sheets [*Nature News*, 2014].

International and national institutions such as the Arctic Council, co-management agencies, and regional fisheries organizations (North East Atlantic Fisheries Commission, Northwest Atlantic Fisheries Organization, and North Atlantic Marine Mammal Commission) can play a critical role as boundary organizations to bring various subgovernmental (e.g., villages, states, and provinces) and nongovernmental actors (e.g., Inuit Circumpolar Council) together to ensure the exchange of information and knowledge [e.g., *Hovelsrud et al*., 2011; *van Oort et al*., 2011], about the impact of changing sea ice conditions and about the impacts of the broad international changes occurring at an increasingly faster pace.

5. Summary and Conclusion

Arctic sea ice interacts with its local environment—the ocean below and the atmosphere above—and the regional and global climate in myriad ways that have important ramifications for biology as well as human activities in and near ice-infested regions. These interactions, particularly with the ocean and atmosphere, are complex. For example, links have been made between the summer sea ice loss and a warmer, wetter autumn atmosphere [e.g., *Serreze et al*., 2011, 2012], changes in atmospheric circulation in the Arctic [e.g., *Overland and Wang*, 2010] and warming and freshening of the upper ocean [e.g., *Maslowski et al*., 2012; *Steele et al*., 2011; *McPhee et al*., 2009]. There are also potential emerging connections between Arctic sea ice and midlatitude weather patterns [e.g., *Francis and Vavrus*, 2012; *Overland and Wang*, 2010].

Summarizing the broad body of research on these interactions is beyond the scope of this paper. Our aim here is to review new findings on Arctic sea ice since the drafting of the SWIPA report (which was substantially drafted in 2009, with final publication in 2011 that included some updated material), which focused on observations of the physical changes in sea ice, comparisons with models, feedbacks, and impacts on biology and human activities in the Arctic. Any such review of new sea ice observations and research is a challenge because of the rapid pace of change in the Arctic and the development of new observational and modeling capabilities. Just in the last 2 years, there has been a notable summer cyclone that led to an unprecedented (in the satellite record since 1979) rate of sea ice loss during the month of August 2012 [*Zhang et al*., 2013; *Parkinson and Comiso*, 2013; *Simmonds and Rudeva*, 2012] followed by a record low-minimum extent. The extreme year of 2012 was followed by a more moderate 2013, with extents well below normal, but substantially (nearly 50% in September) higher than in 2012. These large swings demonstrate the high interannual variability of Arctic sea ice and pose a challenge for sea ice forecasting.

In the midst of these rapid changes in Arctic sea ice, there has been significant progress in data resources and methods. These particularly include new sea ice thickness estimates from new sensors (CryoSat-2 and SMOS) and methods (infrared radiance). However, key gaps remain, most notably regarding snow cover on sea ice, though IceBridge and other airborne, as well as in situ data, are making headway. Sea ice models are improving with better resolution and better physics. However, there are still key gaps remain, such as melt pond parameterization and snow characteristics. And many advances in sea ice models have not yet been incorporated into general circulation models. Thus, the CMIP projections of sea ice are not tracking the changes in sea ice extent, thickness, and drift. These century-scale projections, as well as seasonal and decadal forecasting ability, are becoming more critical in terms of understanding the future impacts on Arctic ecosystems and for planning mitigation strategies for human populations living and working in the far north.

More data are becoming available more quickly and being made more accessible to the scientific community, spurring further research and potentially enabling improved forecasting of sea ice [*Kurtz et al*., 2013]. Online journals (e.g., The Cryosphere Discussions) and real-time analyses (e.g., NSIDC Arctic Sea Ice News and Analysis, http://nsidc.org/arcticseaicenews/, accessed 5 April 2013) are becoming important venues to quickly disseminate preliminary research results and obtain quick feedback before final publication in peer-reviewed journals. Such new approaches are not unique to Arctic sea ice, but this transition is particularly relevant to the sea ice research community where change has been so rapid.

Even as new data and methods are being developed, new research questions are emerging. A recent report from the U.S. National Research Council Polar Research Board [*National Research Council*, 2014] highlights many such questions. As these emerging questions and still existing questions begin to be addressed, we hope this review will provide a useful touchstone on the current state of sea ice science. Whether the Arctic sea ice continues to rapidly change or the future trajectory slows in response to natural variability and other factors, the environment is unquestionably in transformation. This transformation will influence the future climate in the Arctic and beyond, and impacts are already being felt by the ecosystems in and near the ice and by humans living and operating in the Arctic.

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