Implications of Arctic Sea Ice Decline for the Earth System

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sea ice impacts, tundra vegetation, polar chemistry, polar greenhouse gas exchanges, Arctic marine mammals, Arctic Ocean primary productivity

Abstract

Arctic sea ice decline has led to an amplification of surface warming and is projected to continue to decline from anthropogenic forcing, although the exact timing of ice-free summers is uncertain owing to large natural variability. Sea ice reductions affect surface heating patterns and the atmospheric pressure distribution, which may alter midlatitude extreme weather patterns. Increased light penetration and nutrient availability during spring from earlier ice breakup enhances primary production in the Arctic Ocean and its adjacent shelf seas. Ice-obligate marine mammals may be losers, whereas seasonally migrant species may be winners from rapid sea ice decline. Tundra greening is occurring across most of the Arctic, driven primarily by warming temperatures, and is displaying complex spatial patterns that are likely tied to other factors. Sea ice changes are affecting greenhouse gas exchanges as well as halogen chemistry in the Arctic. This review highlights the heterogeneous nature of Arctic change, which is vital for researchers to better understand.

Contents

1. INTRODUCTION

Arctic sea ice plays an important role in regulating climate by acting as a barrier between the cold polar atmosphere and the warm ocean. The seasonal maximum ice area occurs at the end of winter in March, and the minimum occurs in September at the end of summer (**Figure 1*a***). Arctic sea ice has declined dramatically during the past several decades and reached a record minimum extent of 3.41 million km^2 on September 16, 2012 (1) (**Figure 1*b***). This represents a 49% reduction relative to the 1979–2000 climatology (2) and caught the attention of scientists as well as the public. In 2013, the minimum was substantially higher (5.10 million km^2) than in 2012, demonstrating the large interannual variability in the system, but it was still well below average. Sea ice is important for flora and fauna and plays a key role directly or indirectly in many processes that operate in the Arctic. This sea ice decline has stimulated research into how changes in Arctic sea ice could affect other components of the Earth system. Topics chosen for this review demonstrate recent advances in our understanding of the effects of sea ice variability and change, from meteorology, oceanography, biology, and chemistry.

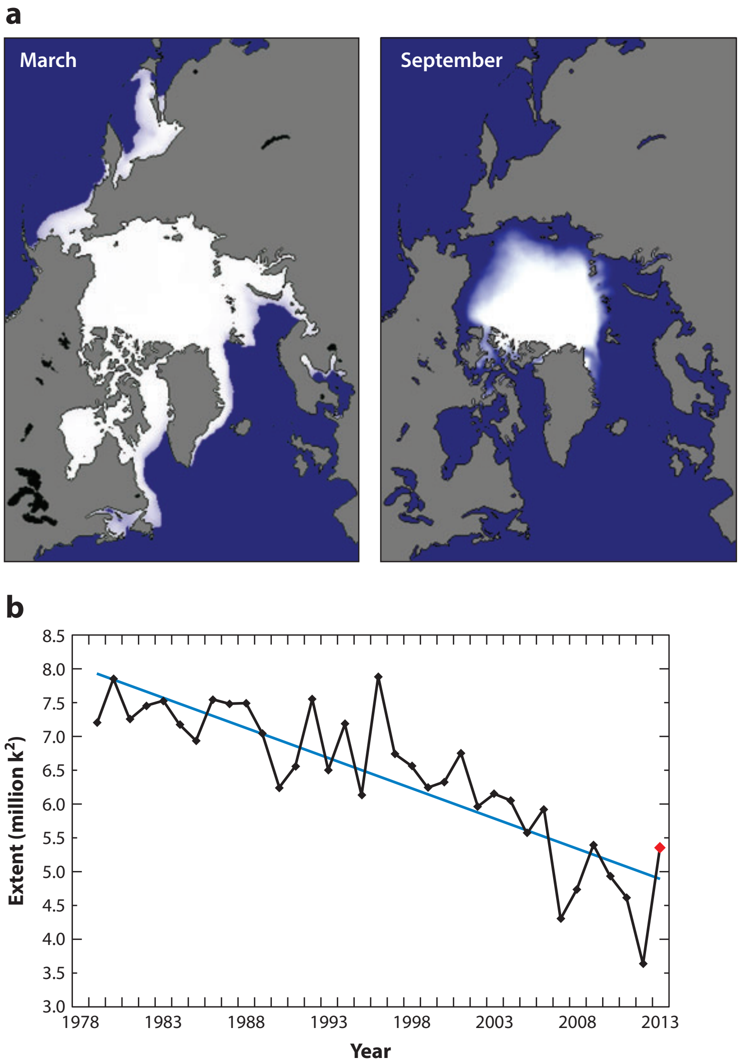
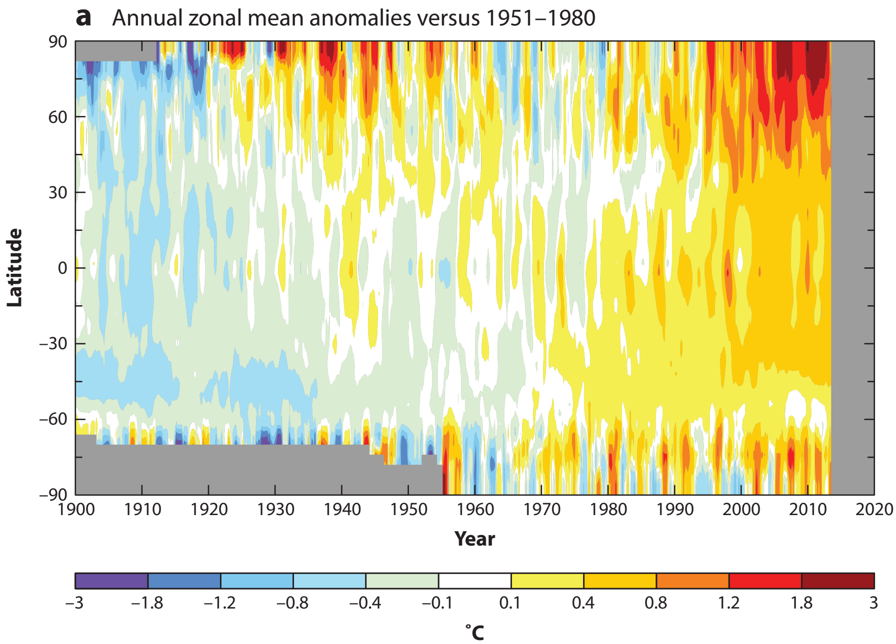


Figure 1

(*a*) Climatology of Arctic sea ice extent from 1981 to 2010 for the annual maximum (March) and minimum (September). (*b*) Monthly average September Arctic sea ice extent annual minima. Both panels used with permission from the National Snow and Ice Data Center (see **http://nsidc.org/cryosphere/sotc/sea_ice.html** for panel *a*; **http://nsidc.org/arcticseaicenews/files/2013/10/Figure3_Sept2013_trend.png** for panel *b*).

1.1. Arctic Climate Change

Zonally averaged temperatures show undisputed warming over the last century (3) (**Figure 2*a***). From 1901 to 2012, global annual mean air temperatures have increased 0.89°C, an increase largely attributed to human activities (4). There is an amplification of warming of Arctic mean annual air temperatures compared with global values (1.36°C per 100 years), and sea ice reduction is important for this process (5, 6). In addition to a long-term secular trend, the Arctic



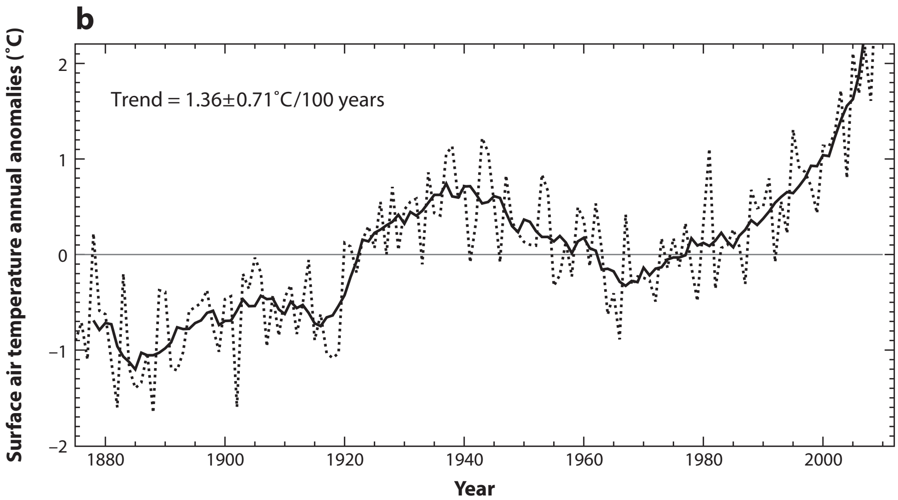


Figure 2

(*a*) Zonal average temperature anomalies from 1900 to 2012 are based on meteorological station data and NOAA sea-surface temperatures. The plot was generated from the NASA Goddard Institute for Space Studies (NASA GISS) website, **http://data.giss.nasa.gov/gistemp**, and details of the data methods are described in Reference 3. (*b*) Annual surface air temperature anomalies (°C) poleward of 59°N, where dotted lines show annual values and solid lines display a seven-year running mean from Bekryaev et al. (5). ©American Meteorological Society. Used with permission. Trend is for the period 1900–2008.

temperatures display large-amplitude multidecadal variability, which can influence trends over short records (**Figure 2*b***). This roughly 60-year cycle is well documented in Arctic air temperatures, sea ice thickness, and ocean temperatures and closely follows North Atlantic variability (7). The large intrinsic climate variability in the Arctic adds complexity to the attribution of trends.

The phenomena of pronounced trends in the Arctic were first noted in the 1960s and are referred to as Arctic amplification (6). Arctic amplification describes the enhancement of air temperature increases and decreases as well as variability relative to global trends and has been attributed to numerous causes. As snow cover and ice area decline, the amount of reflected solar radiation decreases, leading to additional heating of the Earth's surface and increased melting of snow and ice. Arctic amplification also results from increased poleward transport of warm moist air that results from stronger tropical convection in a warmer climate (8). Arctic surface air temperature trends are largest at near-coastal meteorological stations (5), which feel the effect of reduced sea ice more than inland stations. Climate modeling studies show that Arctic surface warming is caused by sea ice decline and associated sea-surface temperatures, whereas warming aloft results from non-Arctic climate forcing (9). Observed temperature trends are largest during autumn and winter (5), and climate models are in general agreement (10). Warming during autumn coincides with the largest seasonal increase of open water, whereas the winter warming is mainly due to the radiative impacts of increased greenhouse gases, increased moisture in the Arctic, and perhaps the trend toward a thinner and more deformable sea ice cover. The effects of sea ice decline are felt most intensely along the coastal Arctic but are also becoming evident farther away, as sea ice retreats to the deep basins of the Arctic Ocean and even through atmospheric teleconnections.

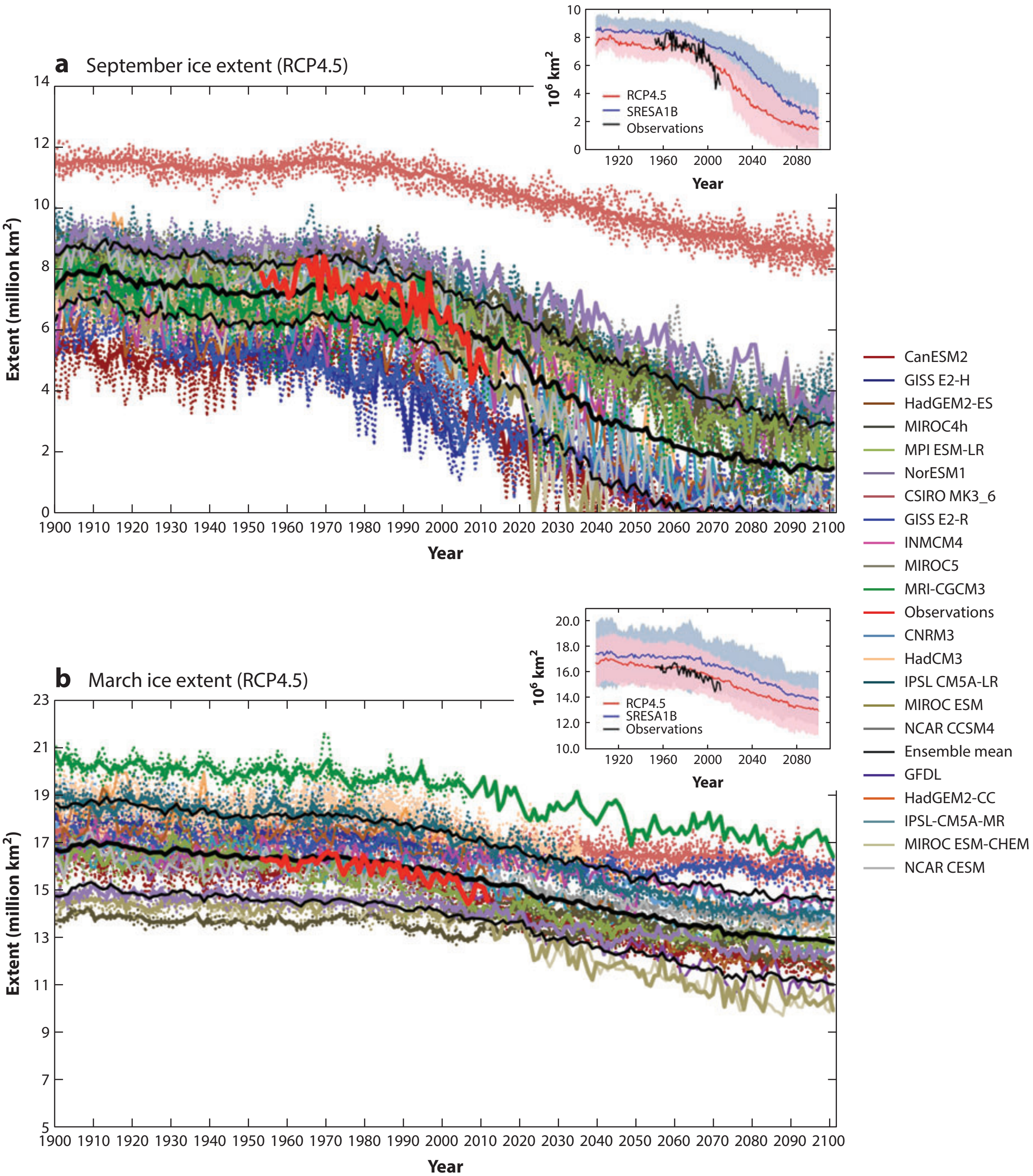
1.2. Goals

This review presents the current state of knowledge of the role sea ice plays in several physical and biological components of the Earth system. Topics covered are limited to allow for reasonable depth in the presentation. The article begins with future sea ice projections and is followed by the impact of sea ice decline on weather and climate. The impact on the ocean circulation, nutrient availability, ocean biota, permafrost, tundra vegetation, and vertebrate fauna are discussed next. The final topics presented are greenhouse gas exchanges and atmospheric chemistry. The review concludes with a summary and conclusions.

2. FUTURE SEA ICE

Coupled Model Intercomparison Project (CMIP3 and CMIP5) studies have prepared projections of future sea ice loss in support of the Intergovernmental Panel on Climate Change (IPCC) assessment (AR4 and AR5) reports. The model projections have been compared to observed sea ice (11, 12) and show a large spread in both their projections and historical extents (**Figure 3**). However, all models show a declining trend in response to greenhouse gas forcing.

The CMIP5 model sea ice extent over the observation period (1953–2011) matches more closely with the observed extent than does that of the CMIP3 models. However, much of the better agreement is due to lower initial historical baseline extents in the models that are more consistent with the observations. The trends in CMIP5 models are still slower than the observed decline. Some of the discrepancy between the models and observations can be explained by the fact that the model projections are based on ensemble averages and thus average out short-term variability. When individual model runs are examined, periods of rapid decline over a few years


a September ice extent (RCP4.5)
Extent (million km²)
Year
RCP4.5
SRESA1B
Observations
10⁶ km²
CanESM2
GISS E2-H
HadGEM2-ES
MIROC4h
MPI ESM-LR
NorESM1
CSIRO MK3_6
GISS E2-R
INMCM4
MIROC5
MRI-CGCM3
Observations
CNRM3
HadCM3
IPSL CM5A-LR
MIROC ESM
NCAR CCSM4
Ensemble mean
GFDL
HadGEM2-CC
IPSL-CM5A-MR
MIROC ESM-CHEM
NCAR CESM
b March ice extent (RCP4.5)

are seen in at least some of the models (13). Thus, the rapid decline in observed extent could be partly due to natural variability that is averaged out in the ensemble model projections. However, various studies indicate that at least 50% of the observed decline is due to external forcing (14–16).

Because of strong interannual-to-decadal natural variability, projecting when the Arctic Ocean will become seasonally ice-free is fraught with uncertainty. CMIP3 models generally suggested that such conditions would not occur until near the end of the twenty-first century at the earliest, but with considerable spread between different models. CMIP5 models move the ice-free date earlier, with some projections by mid-century, but most are later in the century. Wang & Overland (12) constructed projections by selecting a subset of CMIP3 and CMIP5 models that agreed with observed trends and found that seasonally ice-free conditions (using a threshold of <1 million km^2) are projected by around 2040 with a $+/-$ one decade uncertainty.

The rate of ice cover thinning is an important component in the uncertainty of the projections. Analysis of observed and model ice thickness or volume clearly shows a strong thinning trend in recent decades (e.g., 17, 18). This is one explanation for periods of rapid ice loss in the models—extent declines slowly until large areas of the ice cover thin to a certain threshold where they can melt completely during the summer (13). In fact, summer sea ice may become less predictable as thinning continues because the ice cover becomes more sensitive to the summer weather conditions (19). This was likely a factor in the contrasting minimum ice extents in 2012 and 2013.

Maslowski et al. (20) used a high-resolution coupled ice-ocean model to project that ice-free conditions could occur within a decade if the model volume trends over the previous decade continue. However, such extrapolation projections ignore the strong natural variability in the historical record. Even under increased greenhouse gas forcing, increasing trends lasting up to two decades are still possible owing to this variability (15).

Thus, projections of future Arctic sea ice show a clear long-term decline with a seasonally ice-free Arctic inevitable under increasing greenhouse gas forcing. However, strong natural variability along with uncertainties in future forcing scenarios and limitations in the models result in large uncertainties, particularly on decadal timescales.

3. ATMOSPHERIC IMPLICATIONS OF SEA ICE DECLINE

Because the atmospheric circulation is ultimately driven by horizontal gradients of temperature and by processes involving moisture, larger-scale impacts of an ice-diminished Arctic are plausible. Two mechanisms have recently been proposed for linking sea ice to the large-scale circulation affecting middle latitudes. The first is based on the impact of Arctic warming on the pressure (geopotential height) fields, which subsequently leads to an increased frequency of blocking in middle latitudes. The second is an Arctic–midlatitude connection via an impact of the reduced sea ice cover on Eurasian snow cover. Both mechanisms are rooted in the surface heating patterns

Figure 3

Historical and projected sea ice extent for (*a*) September and (*b*) March for the CMIP5 low-emissions RCP4.5 scenario. Shown are observations (*thick red*), average of models (*thick black*), model one standard deviation (*thin black*), and individual models (*colored lines*). The inset images show the observations (*black*), model averages, and one standard deviation range for the CMIP5 (*red/pink*) RCP4.5 and the CMIP3 (*blue/light blue*) A1B scenarios. Figure is from Stroeve et al. (11) and is used with permission from American Geophysical Union and John Wiley and Sons. (Abbreviations: CMIP, Coupled Model Intercomparison Project; RCP, representative concentration pathway.)

that determine the three-dimensional atmospheric pressure distribution, which in turn drives the atmospheric circulation.

3.1. Impacts on Geopotential Heights and Blocking Events

Extending the analysis of Overland & Wang (21), **Figure 4** shows the zonal mean temperature and geopotential heights for 2007–2012, plotted as departures from the 1971–2000 averages, as functions of latitude and height (pressure) in the atmosphere. The 2007–2012 period was one of greatly reduced summer/autumn sea ice coverage. **Figures 4*a,c*** and **Figures 4*b,d*** are for October–November and January–February, respectively. It is apparent that the strongest warming is in the Arctic and is surface-based, confirming the importance of sea ice loss in the recent warming. The warming is more widespread during October–November, when weak stratospheric cooling is also apparent. During January–February, the warming is again surface-based, although values exceeding 2°C are confined to the lower troposphere over 70–85°N. The southward shift of the maximum warming in winter is consistent with the southward migration of the sea ice edge from autumn to winter.

Heating of the lower atmosphere can be expected to raise the pressures aloft by thermal expansion, which increases the thickness of the air column between two pressures. **Figures 4*c,d*** show that pressures have indeed increased aloft above the latitudes of warming in the Arctic. Because the changes in geopotential height (pressure) reduce the normal north-to-south gradient of pressure, the zonal winds weaken. **Figure 5** shows a time series of the average zonal wind speed at 500 hpa for the late autumn/early winter period, October–December (red line). The correspondence with the decrease of autumn sea ice area is apparent in the last few decades, as one would expect if Arctic heating driven by sea ice loss is contributing to the reduction of westerly winds. However, **Figure 5** also contains indications of multidecadal variability, with generally low values (comparable to the late 2000s) from the mid-1950s through the 1960s.

As the west-east component of wind speed weakens, the north–south meanders in the atmosphere's jet stream can be expected to become more prominent. Amplified waves with long wavelengths tend to propagate eastward more slowly than shorter, small-amplitude waves. As a result, the more amplified pattern tends to be associated with persistent periods of anomalous and often extreme weather in middle latitudes. Francis & Vavrus (22) show that zonal wind speeds have indeed decreased and wave amplitudes have increased over the period since 1979 during winter as well as autumn, especially in the North Atlantic sector. Slower wave propagation is consistent with increased incidence of blocking episodes in which large-amplitude waves (often with closed pressure centers embedded in the highly amplified waves) effectively block the eastward propagation of the upper-air features that dictate surface weather regimes. However, Screen & Simmonds (23) show that conclusions about such changes are sensitive to the metric of wave activity and to the choice of geographical region. Barnes (24) came to a similar conclusion and also found that the frequency of blocking has shown no significant increase in the post-1980 period, whereas Hopsch et al. (25) concluded that relationships between autumn sea ice and the winter atmospheric circulation "are not yet robust enough from a statistical perspective" (p. 1). Nevertheless, modeling studies provide additional support for the association between Arctic warming and colder winters over the United States and much of Eurasia. For example, Honda et al.'s (26) model experiments showed that reduced ice cover north of Siberia also leads to abnormally cold temperatures over much of Eurasia, including Japan, during the winter months. However, it must be emphasized that the Arctic–midlatitude connection is complex (27), especially because it is nonlinear and likely involves a combination of convective processes over the Arctic's open water during autumn as well as baroclinic and barotropic processes on the larger scale (28).

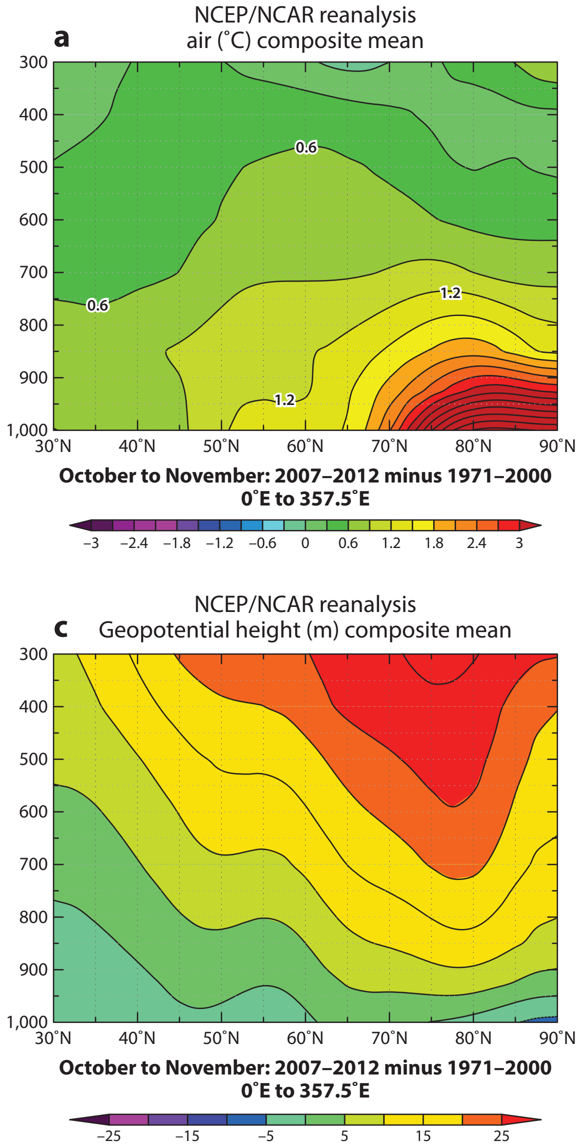


Figure 4

Latitude-height cross-section of the temperatures of 2007–2012 (50–90°N) relative to means for 1971–2000. (*a*) October–November; (*b*) January–February. Lower panels: As in upper panels, but for geopotential heights in (*c*) October–November and (*d*) January–February. January–February panels are for 2008–2013, the years of the winters following the autumns of 2007–2012. Source: NOAA Earth System Research Laboratory, National Centers For Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis.

3.2. The Arctic–Midlatitude Connection via Terrestrial Snow Cover

Model studies and observational data analyses have indicated that reduced Arctic sea ice during autumn is associated with an increase of snow cover over Eurasia (29). The expanded area of open water during autumn represents an enhanced source of moisture for the atmosphere. These studies

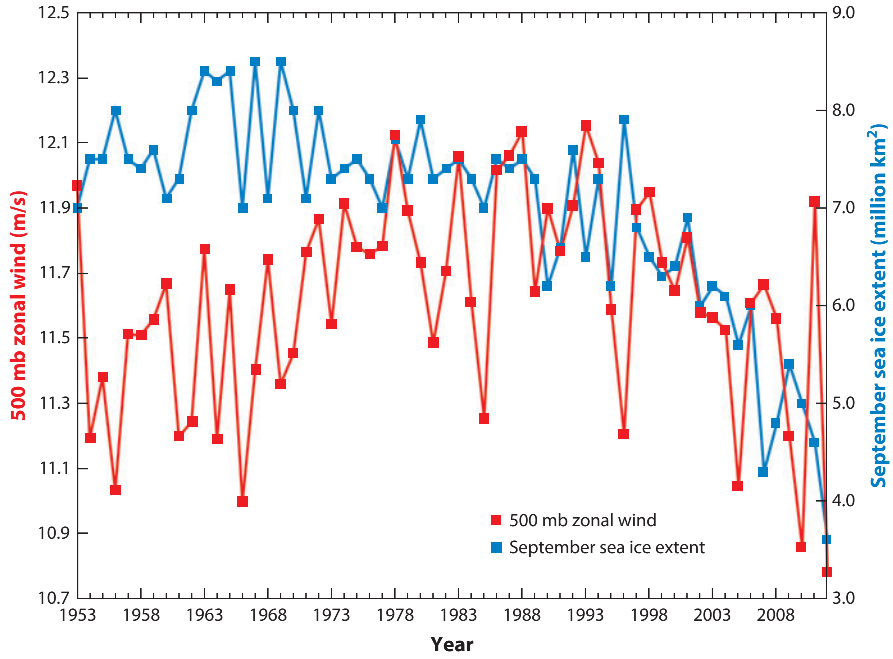


Figure 5

Red line shows yearly values of October–December zonal (west-to-east) windspeeds (m/s) at 500 hPA (mb) averaged over 30–70°N; blue line shows September sea ice extent (millions km^2). Time period is 1953–2012, inclusive. [Sources: NOAA Earth System Research Laboratory, National Centers For Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis (zonal winds) and Reference 139 (sea ice extent).]

have taken the connection further by showing correlations between autumn sea ice/snow cover and wintertime anomalies of snow cover, atmospheric circulation, and air temperature. For example, Liu et al.'s (30) observational data analysis showed that a decrease of autumn sea ice coverage by 1 million km^2 is associated with a 3–12% increase in winter snow cover over the northern United States and parts of Europe and eastern Asia. Negative temperature anomalies similar to those found by Honda et al. (26) were observed over the same regions. The corresponding winter atmospheric circulation anomaly resembles the negative phase of the Arctic Oscillation, with a warm Arctic, colder middle-latitude land areas, and an increased incidence of blocking, consistent with the findings described in Section 3.1. Liu et al.'s observationally based findings were supported by experiments with a global atmospheric model.

More recently, Cohen et al. (29) have presented a synthesis of observational records from the late 1980s through 2010, showing statistically significant trends in September sea ice extent, autumn Arctic tropospheric moisture, October Eurasian snow cover, and the winter (December–February) Arctic Oscillation index. Cohen et al. argue that these significant trends are related. The linkage with the Arctic Oscillation, especially across seasons (autumn ice/snow versus winter Arctic Oscillation) is perhaps the most tenuous link in the causal chain. Dynamic mechanisms involving stratosphere–troposphere connections have been proposed to explain the linkage between the autumn surface state and the winter atmospheric circulation (e.g., 31).

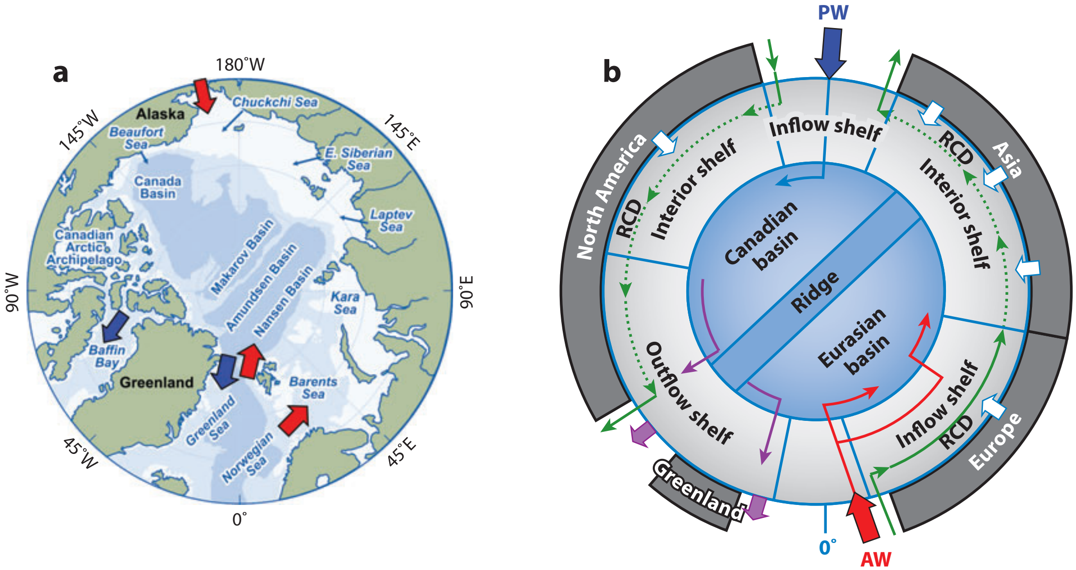


Figure 6

Simplified Arctic bathymetry and place names (*a*) and highly idealized typology of the Arctic Mediterranean based on its hydromorphological domains (*b*). Abbreviations: AW, Atlantic water; PW, Pacific water; RCD, Riverine Coastal Domain; arrows denote component flow directions. Panel *a* is from Carmack & Wassman (140) and published with permission from Elsevier Publishing. Panel *b* is from Bluhm et al. (B.A. Bluhm, N.K. Kosobokova, and E.C. Carmack, manuscript under revision).

4. OCEANIC IMPLICATIONS OF SEA ICE DECLINE

4.1. Oceanic Circulation and Water Mass Properties

Rapid change of Arctic marine systems—linked to dramatic seasonal retreat and thinning of sea ice (cf. 11)—has been observed in the first decade of the twenty-first century (32). This section briefly reviews changes in ocean circulation and water mass properties. To understand these ongoing and extraordinarily fast changes, and the linkages among the physical and biogeochemical components, requires a scale-dependent and regional approach to processes operating within the Arctic marine system as well as knowledge of its two-way connection with the global climate system.

The response of the Arctic Ocean to climate forcing is not uniform across its full extent but rather must be interpreted in terms of regional distinction. To address regionality within the Arctic Ocean, Bluhm et al. (B.A. Bluhm, N.K. Kosobokova, and E.C. Carmack, manuscript under revision) proposed a domain typology based on physiography and hydrography to distinguish among distinct shelf and basin types and their response to forcing [**Figure 6**; see also Carmack & Wassman (140)]. They note that about half of the area of the Arctic Ocean ($\sim 10 \times 10^6$ km^2) is shallow continental shelf and half is deep basin. Shelves may be distinguished as (*a*) inflow shelves (the Barents and Chukchi, which receive oceanic inflows from the Atlantic and Pacific, respectively), (*b*) interior shelves (the Kara, Laptev, East Siberian, and Beaufort, which are strongly influenced by river discharge), and (*c*) the outflow shelves (Canadian Arctic Archipelago and East Greenland, which process waters destined to reenter the sub-Arctic Atlantic). The two main basins, separated by the Lomonosov Ridge, are largely distinguished by the absence (Eurasian Basin) or presence (Amerasian Basin) of Pacific water within the halocline (33).

Changes in water properties and flow derive from both far-field and near-field effects. Within the deep Arctic basins, the water column has warmed to depths exceeding 800 m owing to warmer waters entering from the Atlantic (34, 35) and Pacific (36, 37) Oceans. As water warms and sea ice retreats, it opens the ocean to increased solar radiation and wind exposure; as sea ice thins, its response to wind forcing increases, resulting in greater ice drift velocities (38, 39).

Change in the velocity of ice drift—and thus increased coupling between the wind and ocean currents—is also drawing more warm Pacific water into the western portion of the Beaufort Gyre (36) and affecting the speed and direction of the Circumpolar Boundary Current in the Nansen Basin (40). Increased ice melt combined with wind-driven surface convergence has substantially freshened the Beaufort Gyre (41, 42). This freshening, combined with sea ice retreat and decreased albedo, has allowed formation of a near-surface temperature maximum below the freshened surface in the upper 10–20 m (43, 44), with consequences for oceanic heat release to the atmosphere in autumn.

4.2. Ocean Biology

4.2.1. Marine nutrient flow. As sea ice retreats and thins, it opens the ocean to increased solar radiation and wind exposure, with two main biological consequences. An example of the seasonal cycle of production in the marginal ice zone of the Barents Sea and consequences of an extended growing season are shown in **Figure 7**. On the one hand, increased light will act to increase primary production in areas previously sheltered by perennial ice cover (45). On the other hand, a corresponding increase in new, or harvestable, production requires an attendant supply of nutrients (46). With regard to the latter, ice retreat may increase nutrient supply by allowing increased shelf-break upwelling of nutrient-rich deep waters (47).

Changes in physical parameters will cascade through biological systems (cf. 32). For example, in the Canada Basin, spin-up of the gyre—associated with greater ice drift velocities (38)—has deepened the chlorophyll-maximum layer, which forms annually in the halocline atop the Pacific waters (48). The increase in stratification caused by upper-layer freshening and ice melt constrains the upward flux of nutrients; this reduction in nutrients has affected the food web, as shown by a shift in phytoplankton cell size that favors the smaller picoplankton over nanoplankton (49). This transition to smaller phytoplankton cells may subsequently affect the efficiency of energy-flow pathways through the entire food web as well as the sequestering of carbon to the deep ocean; such a shift may favor a low-energy system characterized by jellyfish blooms as opposed to a high-energy food web characterized by fish and marine mammals.

The ecosystem has been further modified by sea ice reduction and the significant input of sea ice meltwater because of their influence on the carbonate system. Global ocean acidification has been exacerbated in the Canada Basin by the buildup of sea ice meltwater, which has low values of carbonate ions, which in turn affect the solubility of calcium carbonate and the ability of marine calcifying organisms to produce calcium carbonate shells or exoskeletons. This change particularly affects organisms such as the larvae of shell-forming pteropods that are concentrated in the upper 50 m. This solubility shifted in 2008 as surface water tipped from an environment that enabled the formation of shells to one in which dissolution occurs (50). In the Canada Basin, the northward retreat of the ice edge in summer and open ocean conditions now allow upwelling-favorable winds to transport nutrient-bearing Pacific-origin waters onto the continental shelf, thereby increasing primary production (cf. 47, 51). But Pacific waters are also corrosive because of the remineralization of organic matter upstream on the Bering/Chukchi shelves (52). The upwelling of these waters onto the shelf may affect benthic communities of mussels and clams, and perhaps the people who rely on their harvest for subsistence.

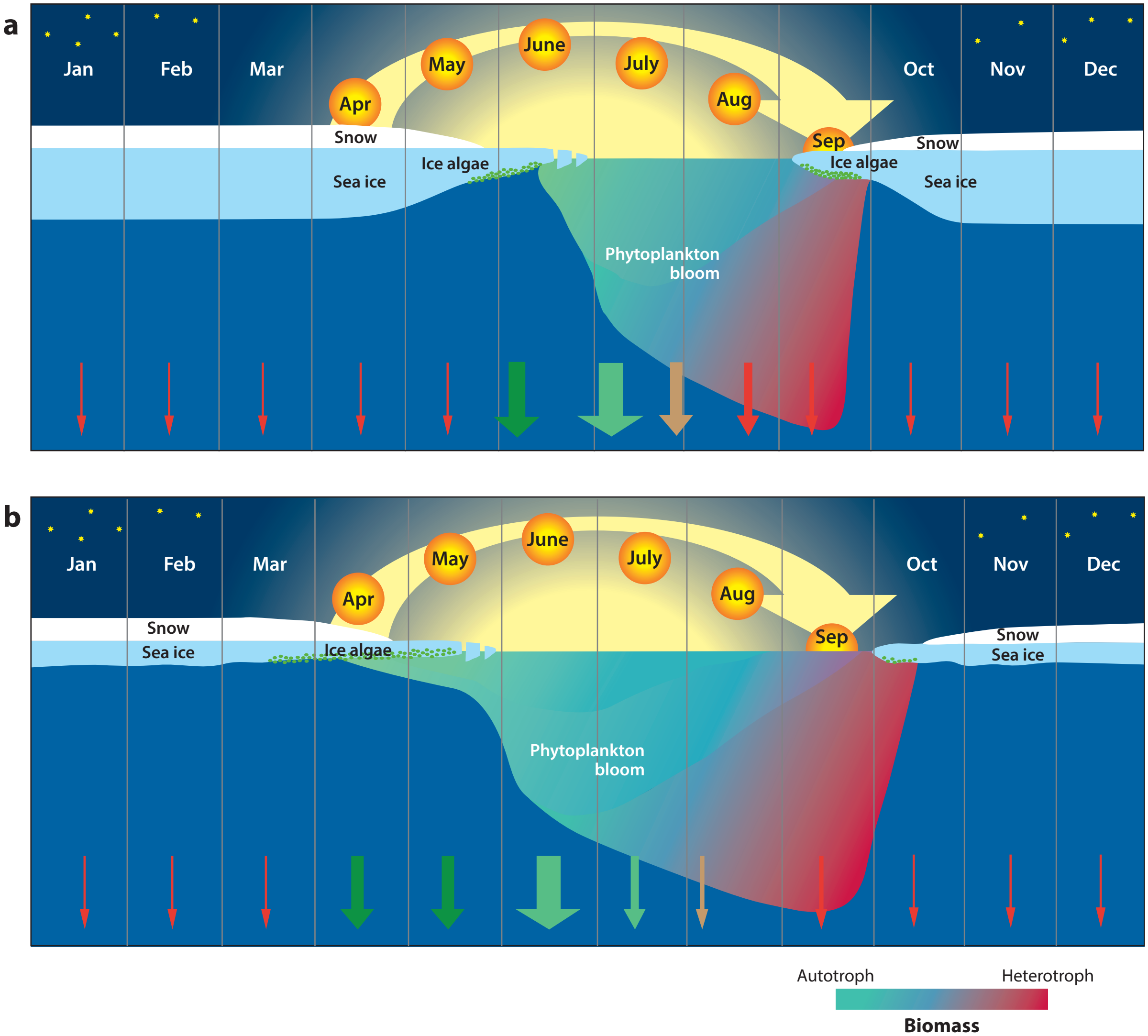


Figure 7

Seasonality in bloom development and in downward carbon export in the marginal ice zone under (*a*) present-day climate and ice conditions and (*b*) a future warmer climate with thinner ice in winter, more melting of summer ice, and a widening of the seasonal ice zone. The green-to-red gradient indicates the balance of suspended biomass from autotrophic to heterotrophic sources. The new and export production in both scenarios is similar because stratification limits nutrient availability. The width and color of the vertical arrows illustrate the semiquantitative magnitude and key composition of vertically exported organic matter [*dark green* = ice algae–derived carbon; *light green* = phytoplankton-derived carbon; *orange and red arrows* = increasing degree of detritus (nonliving particulate organic material)]. Graphic from Reference 141 and reprinted with permission from the Oceanography Society.

4.2.2. Marine primary productivity. The spring melt and breakup of sea ice strongly drives increases in primary production in the Arctic Ocean, primarily by enhancing light availability through sea ice melt ponds and ultimately through the water column upon sea ice breakup. Shifts in the timing of breakup/freeze-up should therefore have profound consequences for primary production throughout the region. Recent studies document increases in primary production in

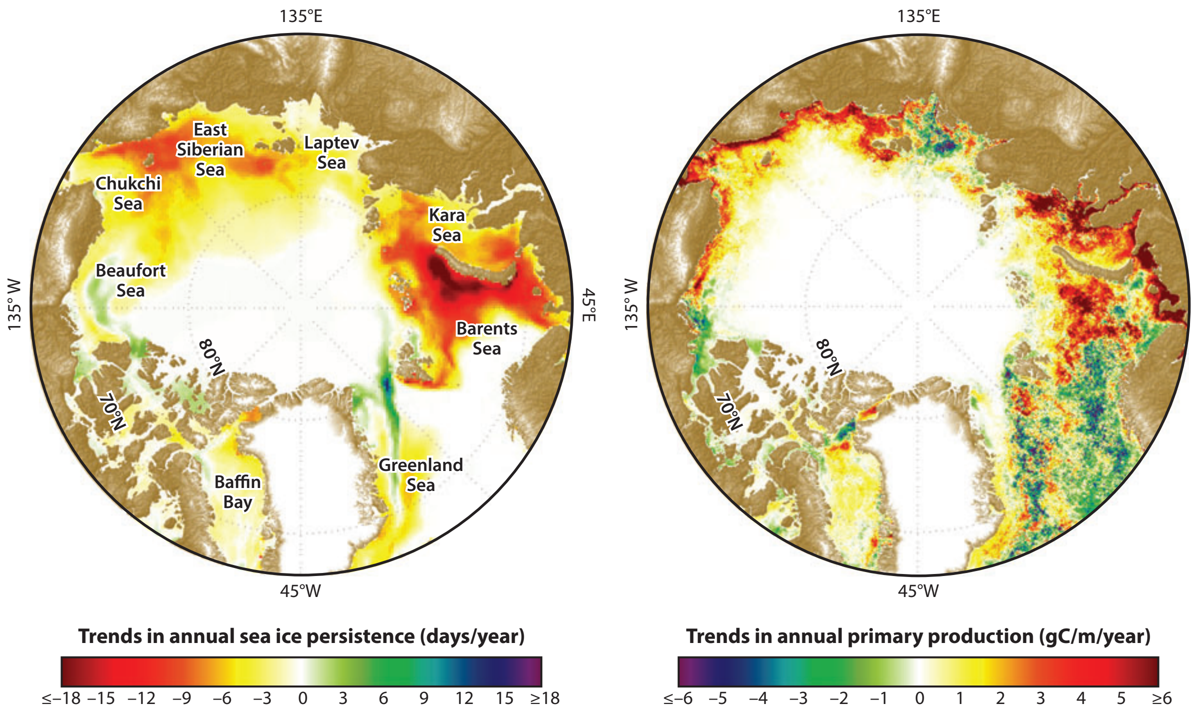


Figure 8

Trends in annual sea ice persistence and total annual net primary production across the Arctic Ocean and its adjacent shelf seas from 1998 to 2009. Sea ice persistence data (based on a 15% sea ice concentration threshold) are derived from Special Sensor Microwave/Imager passive microwave radiances, and primary production data are from Reference 53. Plot is from Reference 142 (gC, grams of carbon).

some sectors of the Arctic Ocean, in addition to shifts in the timing, size structure, and species composition of phytoplankton blooms. Furthermore, new models and empirically based extrapolations point toward overall increases in primary production with further climate warming and sea ice declines, although responses are likely to be very spatially heterogeneous and dependent upon multiple confounding factors. In addition to total primary production, a distinction exists in the ratio of recycled versus new production, with the latter dependent on nutrient supply and representing fixed carbon available to higher trophic levels.

Satellite observations of primary production in the Arctic Ocean over a 12-year period (1998–2009) reveal a ∼20% overall increase, resulting primarily from increases in open water extent (+27%) and duration of the open water season (+45 days) (53). However, no statistically significant secular trend in net primary production per unit area was found, stressing the overall importance of sea ice decline in driving these observed trends. Of the eight geographic sectors of the Arctic Ocean investigated (**Figure 8**), four exhibited statistically significant trends in primary production over the 12-year time period: Greenland (−13%), Kara (+70%), Siberian (+135%), and Chukchi (+48%) seas. For the Arctic Ocean as a whole, annual phytoplankton primary production averaged 493 ± 41.7 teragrams of carbon (TgC) per year over the 1998–2009 period (based on direct satellite observations), as opposed to an estimate of 438 ± 21.5 TgC/year over the 1979–1998 period (based on linear relationships with open water extent). However, these overall estimates are likely conservative, as they do not account for potential productivity that may occur within or beneath sea ice cover.

New observations of the timing, size structure, and species composition of phytoplankton blooms in the Arctic Ocean also show significant changes. Kahru et al. (54) show significant trends toward earlier phytoplankton blooms for 11% of the area of the Arctic Ocean that is observable with satellite imagery over the 1997–2009 period. Areas experiencing earlier blooms are also areas roughly coincident with trends toward earlier sea ice breakup during early summer. In some of these regions, peak blooms in phytoplankton production have advanced from September to early July (a shift of up to ~50 days). Increased ocean stratification resulting from upper-layer freshening and ice melt limits nutrient availability in the productive upper layer and is linked to a shift toward smaller phytoplankton cell size (49).

In addition to phytoplankton primary production, sea ice algal production is also important to consider in the overall Arctic Ocean system. During periods of sea ice cover, total primary productivity is generally relatively small compared with estimates in open seas. As such, the central Arctic Ocean (with its historically multiyear ice cover) is one of the least productive marine regions on Earth, with annual primary production rates estimated at ~14 $gC/m^2/year$. However, during periods of ice cover, primary production by sea ice algae can be an important contributor to these overall production rates. Annual estimates of the contribution of sea ice algal production to total production varies, with lowest contributions in the shelf seas (<10%) and highest contributions in the central Arctic Ocean (>50%) (55).

New models and studies additionally give insight into future trends in Arctic Ocean primary production. Although general increases in primary production for the Arctic Ocean are predicted, trends are expected to be spatially heterogeneous and dependent upon several confounding factors. For instance, models presented by Slagstad et al. (56) suggest that although some Arctic shelf seas may see significant increases in primary production with further sea ice declines, the central Arctic Ocean may see smaller increases in production (owing to low nutrient concentrations), areas newly outside the seasonal ice zone may see decreases in production (owing to increased stratification with atmospheric warming), and inner coastal shelves may see little increases in production (owing to the enhanced delivery of light-inhibiting river-derived material to this region). Empirically based extrapolations presented by Arrigo & van Dijken (53) show that when the Arctic sea ice cover during summer minimum falls to zero, total annual primary production could reach ~730 TgC/year (a ~48% increase over the 1998–2009 average). However, this value is highly dependent upon future distributions of nutrients, the extent of warming-induced enhanced stratification, and other limitations to primary production such as river-associated turbidity in coastal regions.

4.2.3. Marine mammals: ocean sentinels. The effects of climate change, especially recent dramatic reductions in sea ice area and thickness, on Arctic marine mammals was the focus of a special issue of *Ecological Applications* and included (*a*) conceptual models of anticipated changes to prey availability, (*b*) an overview of the effects on animal health, (*c*) the development of a species sensitivity index, and (*d*) an assessment of impacts on various species based on their ecological reliance on sea ice (57 and references therein). The impact of sea ice decline on marine mammals can be framed by their reliance on it for key life history stages (**Figure 9**). Ice-obligate species, such as polar bears, walruses, and some seals, rely on sea ice as a platform for hunting, birthing, and rearing young. Other seal species, although fully adapted to sea ice habitats, have demonstrated the ability to reproduce and feed from shore and so are considered ice-associated, rather than -obligate, species. The three endemic Arctic cetacean species are also ice associated, and at least five cetacean species migrate to and occupy Arctic habitats primarily during the productive summer–autumn season.

Since the development of the ecology-based conceptual model, ongoing research has suggested that ice-obligate species may be losers and seasonally migrant species may be winners in the current era of rapid sea ice decline (58, 59). Evidence for this includes (*a*) increased mortalities and

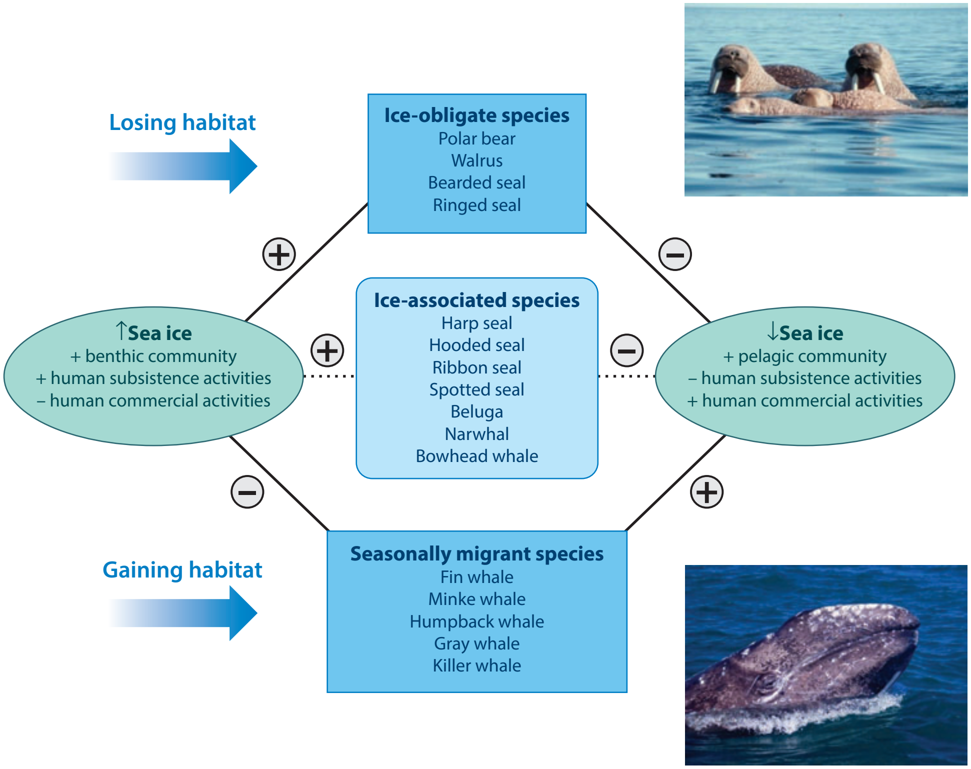


Figure 9

The response of marine mammal species to sea ice loss is mediated by their reliance on it for key aspects of their life history. The dramatic loss of sea ice area and thickness over the past decade has stressed some populations of ice-obligate species (losers) but apparently been advantageous for seasonally migrant species (winners). In all cases, species-specific responses appear to vary by region (e.g., 59). Modified from Reference 57 and used with permission of the Ecological Society of America.

energetic costs of foraging from terrestrial rather than sea ice haul-outs by Pacific walruses (60, 61) and (*b*) negative impacts on ringed seal body condition related to the loss of land-fast sea ice (62). Conversely, seasonally migrant cetaceans appear to find greater and longer access to feeding habitat with sea ice decline. For example, recent observations suggest humpback, fin, and minke whales now routinely join gray whales feeding in the southern Chukchi Sea from summer through early autumn (63), and reports of killer whales in Arctic seas are on the rise in some sectors (64).

Changes in ecosystem productivity associated with sea ice decline are likely already affecting marine mammal populations and are arguably the highest priority unanswered question for upper trophic species (65). Marine mammals, along with marine birds and fishes, reflect ecosystem alterations via shifts both in range, foraging areas, and migratory timing (extrinsic response) and via changes to diet and body condition, including pollutant load (intrinsic response) (see **Supplemental Figure 1**; follow the **Supplemental Material link** from the Annual Reviews home page at **http://www.annualreviews.org**). Changes in the migratory timing, feeding areas, and body condition of bowhead whales provide a good example of the capability of marine mammals to act as sentinels of ecosystem changes related to sea ice loss in the Pacific sector. In sum, bowheads appear to be increasing in number, migrating earlier in spring, shifting among feeding habitats,

Supplemental Material

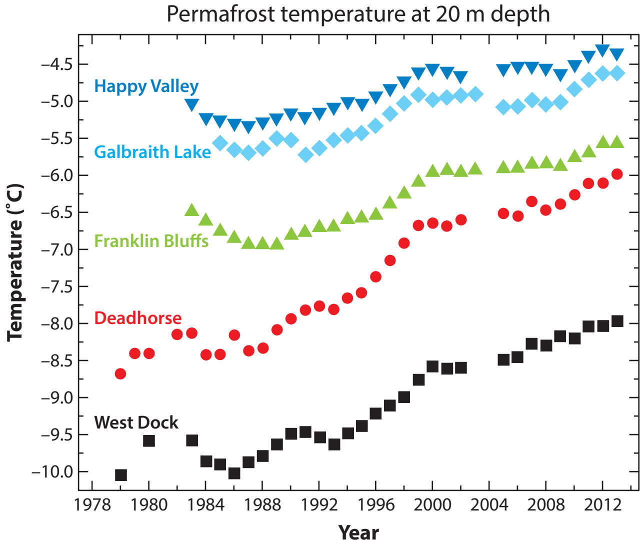


Figure 10

Changes in permafrost temperatures at 20 m depth during the last 30 to 35 years at the West Dock (70.3745°N, 148.552°W), Deadhorse (70.161°N, 148.465°W), Franklin Bluffs (69.674°N, −148.721°W), Galbraith Lake (68.477°N, −149.502°W), and Happy Valley (69.674°N, −148.837°W) permafrost observatories along the Arctic coast and at the long-term University of Alaska permafrost observatories in northern Alaska (updated from Reference 71).

and producing many calves, as well as to be in better body condition (J.C. George, personal communication). This may be a response to more available prey via both productive and advective pathways, as outlined in Moore & Laidre (66). Specifically, diminished sea ice supports more primary productivity, leading to more copepods; furthermore, the dramatic retreat of ice to the deep basin supports both advection of copepods from the slope to the shelf in the Beaufort Sea and of euphausiids through the Bering Strait and onto the Chukchi and the western Beaufort shelf.

5. TERRESTRIAL IMPLICATIONS OF SEA ICE DECLINE

5.1. Permafrost Changes

At any given location, temporal variations in permafrost temperature at interannual and decadal timescales are governed by changes in air temperature and snow-cover depth (67, 68). The correlation between mean annual air and near-surface permafrost temperatures measured during the last half of the twentieth century at several meteorological stations in Siberia is positive and significant (67). Both mean annual air temperature and the winter snow depth in the Arctic coastal areas are likely related to summer sea ice extent. Sea ice decline is indirectly linked to permafrost through subsequent air-temperature and snow-cover increases, discussed above (see Sections 1.1 and 3.2).

Permafrost temperatures at sites in northern Alaska near the Beaufort Sea coast display interannual variability similar to that of sea ice extent (69). This is also borne out in **Figure 10**, which shows permafrost temperature at two Alaskan sites near the Arctic coast (West Dock and Deadhorse) that compare favorably with the Arctic sea ice extent (see **Figure 1*b***). An intriguing feature of Alaskan, Canadian, and Russian permafrost research sites is that larger warming is occurring in areas of coldest (more northerly) permafrost along the Arctic coastal sites rather than at warmer sites in the continental interior (68, 70). This is consistent with the idea of Arctic amplification. As illustrated at selected sites in Alaska (**Figure 10**) and Russia, although temperature has been generally increasing continuously in colder permafrost located close to the Arctic coasts, the temperatures of warmer permafrost in the continental interior have been relatively stable or even decreasing slightly (71). In northernmost Alaska, the most recent data suggest that a coastal warming trend has propagated to the southern extent of the tundra (**Figure 10**), where a noticeable warming in the upper 20 m of permafrost has become evident since 2008 (71). However, permafrost temperatures in Interior Alaska were still decreasing in 2012. These spatial patterns in the temporal variability of permafrost temperatures are consistent with recent declines in the sea ice extent in the Arctic, though clear causality has not yet been established. However, other factors such as the polar climate amplification and the dynamics of unfrozen water in permafrost (70, 72) may also be important.

5.2. Tundra Vegetation

Supplemental Material

The Arctic tundra biome owes its existence to cold summer air masses associated with the ice pack that keeps coastal summer temperatures below that required for tree growth. A polar view (**Supplemental Figure 2**) reveals that the biome is restricted latitudinally to a narrow belt along the northern continental margins and the Arctic islands (73). Eighty percent of the lowland portion of the Arctic lies within 100 km of seasonally ice-covered seas. How will loss of coastal sea ice affect land temperatures and terrestrial ecosystems? The knowledge of vegetation responses along the present-day summer temperature gradient (74, 75), biogeographic history, long-term experiments, and expected continued warming trend suggests extensive changes to the structure of the vegetation that will have cascading effects through Arctic terrestrial ecosystems. Some of these changes are already visible at a circumpolar scale via satellite data.

Plant scientists have long recognized distinctive bioclimate subzones within the Arctic Tundra Zone as a method to categorize the vegetation transitions that occur across the roughly 10°C mean July temperature gradient from the tree line to the coldest parts of the Arctic. This temperature gradient forms the basis of the Circumpolar Arctic Vegetation Map (see 73 and references therein), which uses five bioclimate subzones (**Supplemental Figure 2** inset map). The influence of the coastal temperature gradient is evident in the concentric arrangement of these subzones that centers on the Arctic Ocean. Subzone A is the coldest and most barren subzone, and Subzone E is the warmest and most lushly vegetated. The summer warmth index (SWI, the sum of monthly mean temperatures exceeding 0°C) measures the amount of warmth available for plant growth. The values are calculated from land-surface temperatures and range from 1–6°C month in Subzone A to 20–35°C month in Subzone E. The total phytomass varies from about 65 g/m^2 in Subzone A to 750 g/m^2 in Subzone E (75).

The normalized difference vegetation index (NDVI) is the most common satellite-derived index used to monitor global-scale vegetation productivity (76). The NDVI is interpreted as the photosynthetic capacity of the vegetation (76) or its greenness and has been correlated with ground measurements of biomass and other measures of tundra photosynthetic activity (77). Satellite-based NDVI measurements have a consistent relationship with ground-level measurements of aboveground biomass in the tundra of both North America and Eurasia (78). Linkages between diminishing Arctic sea ice, increasing areas of Arctic ice-free waters, summer land temperature warming, and NDVI increases have been described (79, 80).

Spring sea ice is declining everywhere except in the Bering Sea, while summer open water area is increasing throughout the Arctic (**Figure 11**). The SWI trends from 1982 to 2012 are generally positive but are negative over western Eurasia and in parts of northern Canada (**Figure 11*a***).

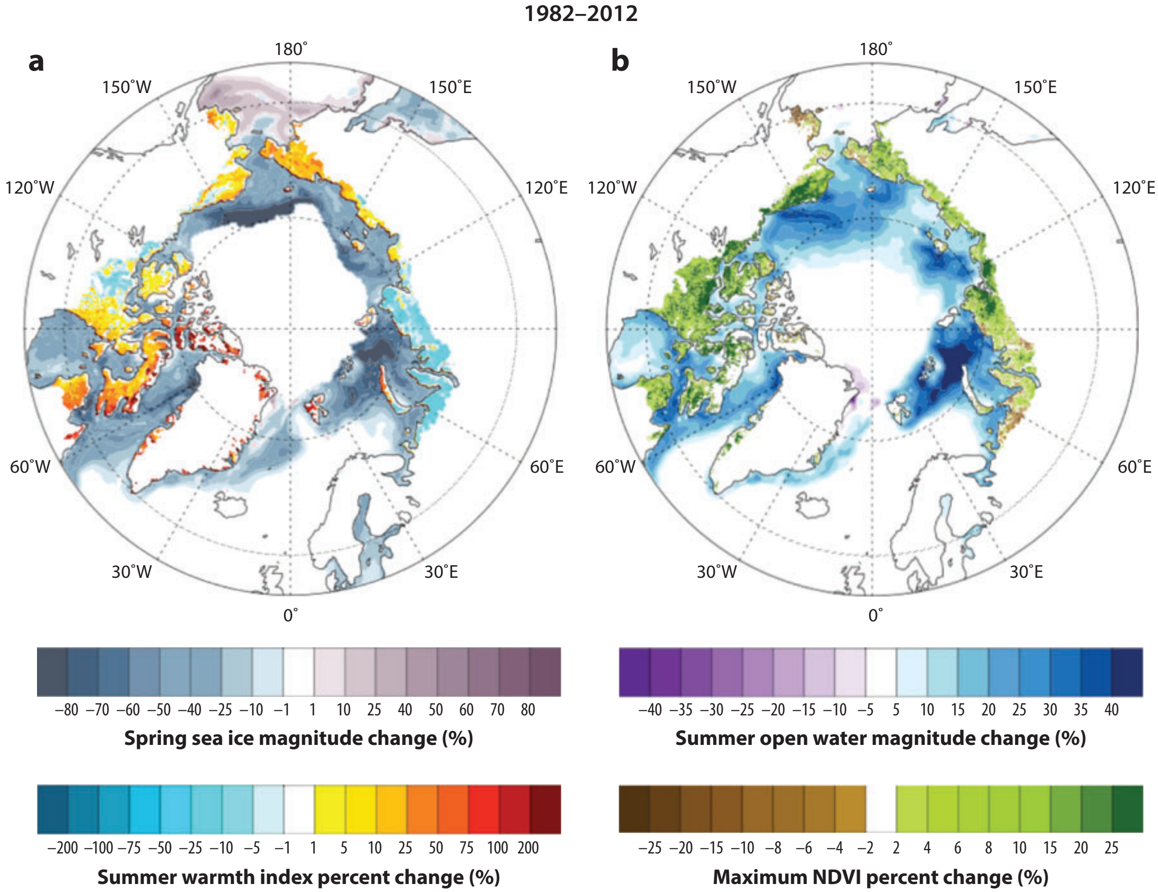


Figure 11

Percent trends (1982–2012) for (*a*) spring sea ice concentration (%) (as represented by trends from the climatological 50% sea ice concentration level) and land-surface summer warmth index (°C month), (*b*) summer (May–August) open water area (%) and annual maximum NDVI (Normalized Difference Vegetation Index; unitless). The percent trend highlights the size of relative changes in the Arctic.

Eastern North America continues to show increased summer warmth and a corresponding steady increase in MaxNDVI (**Figure 11*b***). Positive MaxNDVI trends from 1982 to 2012 are generally weaker compared with trends from 1982 to 2008. There has been a strong acceleration of sea ice decline in Eurasia since 2003, simultaneous with a strong decline in SWI. However, the time-integrated NDVI (TI-NDVI for a given locality is the annual sum of the biweekly NDVI values) has declined since 2005 in Eurasia, consistent with the decline in SWI (80). The recent divergence of previous trends between SWI and NDVI in some parts of the Arctic indicates that the relationships between sea ice retreat, land temperatures, and NDVI are not as simple as originally indicated from earlier data (79). One possible explanation of the recent reversal of SWI trends could be recent changes in large-scale circulation (80). A recent analysis that employed high-resolution NDVI in eastern Siberia found that the correlation between sea ice and SWI and TI-NDVI generally decreased in strength with increasing distance from the coast (81). SWI appears to be driving TI-NDVI in many cases, but not systematically, highlighting the presence of other limiting factors for plant growth. Other studies have also noted the local importance of non-temperature-driven influences on tundra productivity (82), including disturbance-related phenomena such as extensive landslide activity, thermokarst, and reindeer grazing (83). A better understanding of the spatiotemporal relationships between sea ice, land temperatures, vegetation response, and other climate and disturbance factors is needed before we can expect to predict future trends.

Supplemental Material

Subzone A may be the most sensitive to change because of the small area of the subzone, its occurrence almost exclusively on islands, the very sparse vegetation on mineral soils, and the subzone's proximity to sea ice (**Supplemental Figure 2**). If released from summer sea ice, these areas will likely experience very rapid change (84, 85). Areas farther south appear to be less sensitive to change because of the very large area involved; colder, wetter soils that are more buffered to change by thick moss carpets; greater heterogeneity of the vegetation; and the greater distance from sea ice.

5.3. Vertebrate Fauna

The most likely consequences of sea ice decline for animals in the Arctic relate to loss of areal extent, which constitutes critical habitat for ice-obligate and ice-associated species, and an increase in the length of the annual ice-free season (85). Polar bears depend upon sea ice for hunting and denning. Declines in sea ice cover and progressively earlier seasonal timing of sea ice melt have been implicated in shifts in adult distribution (86) and den site selection by female polar bears (87, 88), declines in abundance of polar bears (89), declines in offspring recruitment, and smaller body size (90, 91). At Hopen Island, in the Svalbard Archipelago, a trend toward later annual reformation of sea ice over the past three decades has been associated with a decline in the number of polar bear maternity dens on the island and reduced body mass of adult female bears and cubs (88).

Other ice-obligate Arctic marine species that may experience population declines with continuing loss of sea ice include the Pacific walrus, ice seals (also see Section 4.2.3), and the ivory gull (85, 92). In the western Hudson Bay, the decreasing depth of snow on pack ice and earlier seasonal melting of sea ice have been associated with reduced survival and recruitment of ringed seal pups (93). Because ringed seals, which are the most numerous seal in the Arctic, use stable sea ice and snow dens on ice to protect their pups from predation by polar bears (94), expected trends toward earlier annual melting of sea ice and declining snow depth and cover on sea ice may negatively affect ringed seal populations across the Arctic (95). The endangered ivory gull, which utilizes pack ice edges as habitat for nesting, foraging, and resting throughout the year, has undergone dramatic population declines in portions of its range, presumably because of declining annual minimum extent of sea ice (96, 97).

Although the most intuitive population dynamical and demographic responses to sea ice loss derive from ice-obligate species in marine environments of the Arctic, complex dynamical responses may also arise in terrestrial systems (85). These are most likely to develop through indirect cascading effects of vegetation response to sea ice dynamics and decline, but they may in some instances reflect more direct influences of sea ice variation. For instance, the dynamics of multiple populations of muskoxen along the coast of northeastern Greenland displayed covariation with a snow ablation index that captured local abiotic conditions driven by sea ice flux along the coast (98). On Bylot Island in the high Arctic Canadian Archipelago, top-down control of herbivores has prevented their increase despite a near doubling of primary productivity associated with warming over the past two decades (99). In this system, Arctic foxes are likely able to maintain high levels of resource intake and abundance by utilizing sea ice to forage over large areas (99). Hence, if declining sea ice renders resource acquisition by Arctic foxes more variable, it may eventually alleviate top-down control on the island. Deserving of an immediate research focus is whether more extensive, community-wide consequences of sea ice loss are to be expected, such as the recently documented synchronization of dynamics by extreme weather across an entire food web on Svalbard (100).

6. IMPLICATIONS OF SEA ICE DECLINE FOR GREENHOUSE GAS EXCHANGES AND CHEMISTRY

6.1. Greenhouse Gas Exchanges

6.1.1. Terrestrial and marine CO_2 exchange. Many of the components discussed thus far are closely linked to the exchange of greenhouse gases in the Arctic; such is the case with permafrost thaw and increased plant productivity. The relation to greenhouse gas exchange appears the most straightforward for the latter: Plant productivity has increased with sea ice decline—as was previously discussed in Section 5.2—potentially intensifying the uptake of CO_2 in the Arctic. However, a sea ice–induced rise in temperatures also increases soil respiration—a release of CO_2—and this might nullify an increased uptake by plants. For example, warming can lead to higher plant carbon but simultaneously lower soil carbon, resulting in a zero net change (101).

To detect a change in the net carbon uptake of Arctic ecosystems with sea ice decline, direct measurements of CO_2 exchange with techniques such as flux chambers and eddy covariance can provide much insight. These types of measurements have been increasing steadily in the past few decades (102), but despite these advances, it is often difficult to draw conclusions on the long-term response of CO_2 uptake beyond the site level (103). Most regional-scale models indicate that the net uptake of CO_2 has increased slightly in the Arctic while temperatures rose (102); it thus increased indirectly through sea ice decline.

Although this response seems favorable, the models poorly represent the dynamics of freshwater ecosystems, tundra fires, and coastal erosion (104). Besides, a larger release of CO_2 through permafrost thaw cannot be excluded in the long term (105). It is unclear whether sea ice decline will dampen or strengthen the terrestrial uptake of CO_2 in the Arctic. What is clear, however, is that this part of the Arctic acts as a sink, with estimates of its strength at about -110 TgC/year, with lower and upper boundaries at -80 and -291 TgC/year, respectively (102).

Meanwhile, estimates for the uptake of CO_2 by the Arctic Ocean are, despite the larger surface area, comparable to the terrestrial uptake—about -120 ± 60 TgC/year (106). This estimate is mainly derived from measurements of the difference in the partial pressure of CO_2 (pCO_2) between ocean surface waters and the atmosphere. If the value for pCO_2 is lower in the former, an uptake of CO_2 is made possible. This process is especially important on the shallow Arctic coastal shelves, where the cooling of inflowing waters and large primary productivity maintain a lower pCO_2, and thus an uptake (107). These processes are stimulated by a lower sea ice extent (see also Section 4.3) due to the removal of the sea ice barrier, and this strengthens the uptake of CO_2 in the shallow waters of the shelf margin. However, it has been suggested that these increases cannot be sustained in the deeper waters of the central Arctic Ocean (108). Besides, the increased uptake of CO_2 also leads to ocean acidification, which has its own negative effects on the marine ecosystem (107) (discussed in Section 4.3).

The above picture is complicated by recently discovered processes related to the formation and melting of sea ice itself (109), negating the view that ice acts solely as a barrier. During formation, brine is expelled through channels in the ice. This brine can contain dissolved inorganic carbon, and, because of its high density, this carbon is transported downwards with it. Furthermore, ikaite crystals (hexahydrate of calcium carbonate, $CaCO_3 \cdot 6H_2O$) can form in the ice following these

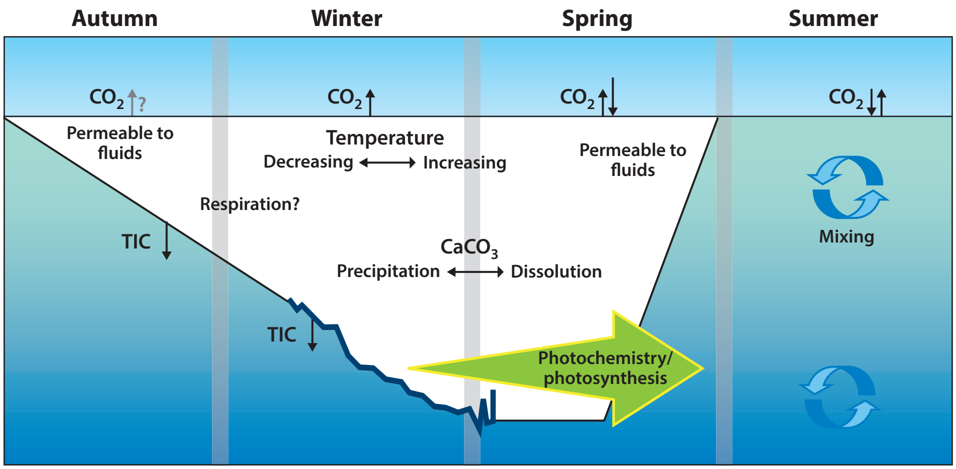


Figure 12

Summary of the various carbon cycling processes related directly to sea ice as they occur throughout the year. In autumn, carbon is rejected together with brine during sea ice formation, which sinks because of its high density. At the surface and throughout the winter, the permeability of the ice is determined by temperature, and the ice–air exchange of CO_2 is governed by the difference in partial pressure of CO_2 (pCO_2) with the atmosphere. During sea ice melt, the dissolution of ikaite crystals within the ice lowers the pH of surface waters, and this stimulates uptake through a lowering of pCO_2. Furthermore, if the ice is thin enough, sunlight can penetrate and stimulate photosynthesis. In areas without sea ice, the exchange with the atmosphere is determined by the pCO_2 difference between the air and the ocean surface. Adapted from Reference 111 and used with permission from the American Geophysical Union and John Wiley and Sons. (TIC, total inorganic carbon.)

processes (110). Upon ice melt, the dissolution of these crystals lowers the pH of surface waters, which in turn lowers the pCO_2. Hence, both processes have the possibility to facilitate carbon uptake. This has important implications for the Arctic as a carbon sink, given that more ice is formed and melted under seasonal ice cover conditions.

A thinner sea ice cover also permits more algae growth (again, see Section 4.3), and the sea ice surface is in direct contact with the atmosphere, allowing for an exchange of CO_2 (111). Areas of open water within the ice pack, such as polynyas, can also be hot spots of CO_2 uptake (112), further complicating the picture. Thus, there are many different processes in and around the sea ice that can lead to an uptake or release of CO_2 (**Figure 12**). Many of these processes are still poorly understood, complicating predictions of the future oceanic uptake of CO_2 in the Arctic.

6.1.2. Terrestrial and marine methane emissions. Although CO_2 is an important sink, methane often gets more attention because the Arctic is a source of this potent greenhouse gas (102). Estimates of methane-emission totals from tundra are about 19 TgC/year, with lower and upper bounds of 8 and 29 TgC/year. The concern is that these emissions will increase following a temperature rise, as warming increases the activity of methanogens and consequently methane production. Methane emissions could therefore increase due to a sea ice–induced warming.

Such an increase in methane emissions seems probable, as a recent intercomparison among models and measurements has shown higher emissions in recent years compared to the 1990s (102). The fact that this occurred concurrent with sea ice decline is not coincidental. Recently, it was revealed that modeled methane emissions show a significant inverse correlation with changes in sea ice extent (103), as shown in **Figure 13**. This implies that a reduction in sea ice will lead to

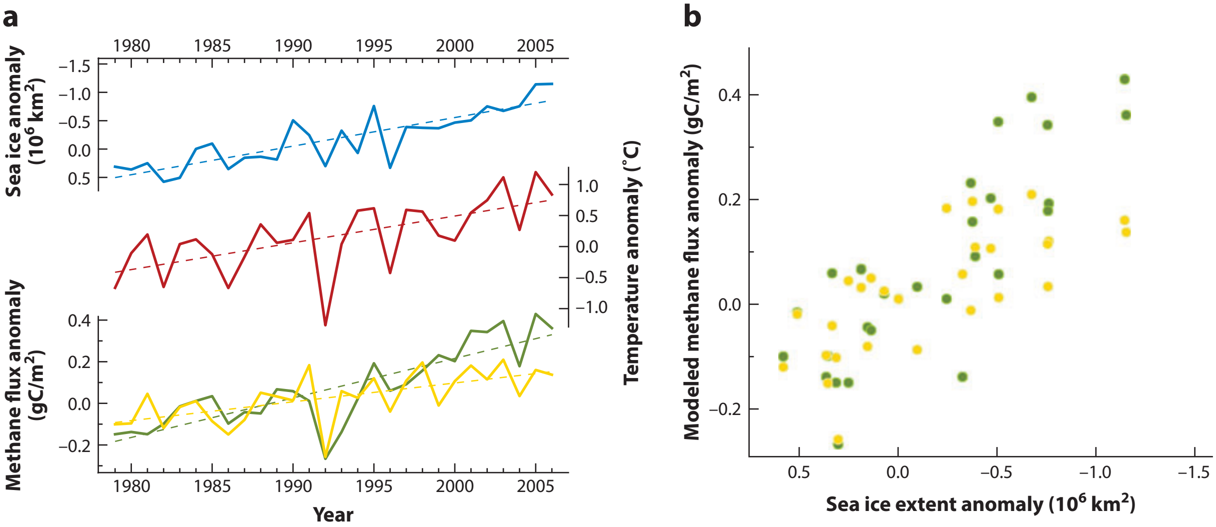


Figure 13

Relationships between sea ice extent (*blue*, plotted inverted), summer temperature (*red*), and methane fluxes from the models LPJ-GUESS WhyMe (*green*) and TEM6 (*yellow*). (*a*) Graphs illustrate how each parameter shows similar trends and interannual variation. (*b*) Sea ice is plotted against the methane models, which shows an inverse correlation (sea ice is plotted inverted). Sea ice extent is courtesy of the National Snow and Ice Data Center, while the methane models are modeled independently from it. Summer temperature shown is the same as the input for the models and retrieved from the CRU TS 3.0 data set. Adapted from Reference 103 and used with permission from Nature Publishing.

higher methane emissions. Unfortunately, because of the observed model spread and uncertainties in wetland extent, it is unclear by what precise magnitude these emissions are expected to increase following sea ice decline.

Terrestrial methane emissions are, nonetheless, better constrained than marine flux estimates, due in part to the logistical difficulty of measuring emissions in the Arctic Ocean. Also, a large variety of sources need to be considered in a marine context, varying from geological seeps of natural gas to deep-water gas hydrates, shallow gas hydrates in subsea permafrost, and in situ production in ocean bottom sediments. Higher ocean temperatures will not affect these sources equally. For example, gas hydrates off the coast of West Svalbard have been releasing methane for thousands of years (113) and have a low impact on the atmosphere (114).

The focus for marine methane emissions lies, therefore, in the same area as for the marine CO_2 uptake: the shallow coastal shelves, where released methane is more likely to reach the atmosphere. Indeed, measurement campaigns have shown that the East Siberian Arctic Shelf releases as much as ∼13 TgC/year (115), comparable in size to the release of methane from the terrestrial Arctic. Although this shows that the Arctic Ocean is an important source of methane, the impact of sea ice decline on this source is yet unclear.

One of the reasons behind this indiscernibility is the slow penetration of heat into the deeper sediments. Much of the current state of the subsea permafrost—and its potential to release methane—is a result of an inundation following sea level rise that started about 8,000 years ago, after the end of the last glacial period (116). The submergence of this area with warm ocean waters—relative to the predominantly low air temperatures—started a degradation of the subsea permafrost that has progressed ever since. An additional warming following sea ice retreat may not impact the stability of the deeper subsea permafrost—and potential gas hydrates—for centuries to come (116). A massive release of methane from hydrates within decades, as suggested elsewhere, is therefore deemed to be highly unlikely (117).

Nonetheless, a lack of a protective ice cover will allow for storms to ventilate the methane-saturated water column more frequently (115), and methane bubbles will be able to reach the atmosphere during longer periods of the year, whereas previously they would have been trapped in the ice. However, many of the underlying mechanisms to the observed fluxes remain to be understood. It is therefore conceivable that sea ice decline will affect marine methane emissions, although the magnitude and timescales are unclear.

6.2. Arctic Climate Interactions with Atmospheric Chemistry

The atmospheric chemistry of polar regions differs from midlatitude processes and is highly seasonal, affecting the fate of gases and pollutants such as ozone, mercury, and organic compounds. A particularly unique season is Arctic spring, when the frozen ocean is covered with sea ice and sunlight returns, reinvigorating photochemistry. During this season, salts from sea ice are converted to reactive halogen atoms (e.g., Br and Cl atoms) (see reviews by 118, 119), and these reactive halogens cause boundary-layer ozone depletion events (ODEs) (120, 121) and mercury deposition events (MDEs) (122, 123). Mercury deposition to snowpack is of concern because it is a toxic metal; however, the linkage between atmospheric halogen–induced mercury deposition and highly toxic organomercury compounds (e.g., methyl mercury) that bioaccumulate in food webs involves many steps and needs study. Sea ice and snow on the ice play key roles in halogen chemistry by providing surfaces on which chloride (Cl^-) and bromide (Br^-) salts are presented to the atmosphere. Atmospheric chemical cycles known as the bromine explosion (124, 125) are generally accepted as the main mechanism of halogen release, although details on what types of snow and ice are most efficient at halogen release are widely debated. Sea ice conditions were thought to be important, and thus much effort has been directed at understanding the dependence of halogen chemistry on sea ice type and the presence of open and/or refreezing leads. McElroy et al. (126) found high levels of reactive halogens in the Arctic troposphere and interpreted these levels as having been influenced by convective pumping of boundary-layer air masses forced upward by sea ice leads (cracks). Rankin (127) proposed that frost flowers (ice crystals that grow on refreezing leads) were the source of reactive halogens, but later work by Simpson et al. (128) indicated that simply first-year sea ice contact was a better predictor of halogen activation than was the potential to form frost flowers. Recent work has confirmed the efficiency of snow in producing molecular bromine and has found that highly saline ice was less efficient (129).

Storms may also play a role in halogen activation, as has been indicated by Antarctic work (130). It is generally considered that a thinning Arctic ice pack that has more leads will increase general salt content of the snow/ice and thus increase halogen activation, but the role of temperature, acidity, and many other environmental conditions may modify the salinity influence. The initiation and termination of halogen events are not well understood and may hold important controls on this chemistry.

Recent studies have shown that snowpack, when illuminated with UV and often when ozone flows through the snowpack, can produce reactive bromine and chlorine precursors (131), possibly acting as an initiator of halogen events. Moore et al. (132) found that ozone and mercury recovered from depleted levels when air masses had recent contact with convection over ice leads, indicating that a future Arctic sea ice state with more leads may bring more ozone and mercury from aloft into contact with sea ice, possibly increasing the mass of mercury available for deposition to snowpack. Few studies have addressed long-term trends in ozone or halogen chemistry, but the recent study by Oltmans et al. (120) found that in the month of March, Barrow, AK, boundary-layer ODEs have been increasing in severity at the same time that summer sea ice reductions have increased the amount of first-year ice and leads upwind of Barrow. It is clear from the seasonality of ODEs that they begin upon return of sunlight after Arctic nighttime (e.g., February to March, depending upon latitude) through the time of snowmelt on sea ice (May to June). The end of season is thought to be caused by a decrease in reactive surface area of the snow, which is necessary for halogen activation. Therefore, shifts in the seasonality of snowmelt or the presence of ice layers by mid-season melt may change available reactive surface area and also modify Arctic halogen chemistry. Overall, it is clear that Arctic sea ice has profound influences on Arctic halogen chemistry, affecting the fate of pollutants such as mercury and key atmospheric chemicals such as ozone and hydrocarbons, and thus sea ice change is likely to affect Arctic atmospheric chemical processes.

7. SUMMARY AND CONCLUSION

Sea ice is projected to continue its decline, but the exact timing of a seasonally ice-free Arctic is unclear due to large-amplitude natural variability, a lack of understanding of system-wide processes controlling sea ice disposition, and uncertainty in greenhouse gas emission scenarios. As sea ice declines, predicting the ice minima will become more difficult due to the increasing sensitivity of ice area to atmospheric forcing and the need for improved summer storm forecasts. Sea ice reductions lead to enhanced surface warming and lowered atmospheric pressures in the Arctic. The polar-amplified warming weakens both the north–south temperature gradient and the upper-level westerly winds. With the weakening of the westerlies, there may be larger north–south meanders of the jet stream, bringing extremes of temperature to the lower latitudes. In recent autumns, exposure of a warmer, fresher ocean has replaced sea ice, providing moisture to enhance Eurasian snow cover. Increases in snow cover have important consequences for moisture availability during the following summer (133), permafrost temperatures, and vegetation greenup. Although the above mechanisms are quite plausible, there is no consensus among climate scientists at present as to whether sea ice decline is causally linked to midlatitude weather extremes or increased snow cover.

Sea ice decline has led to increased primary production in the Arctic Ocean and its adjacent shelf seas by enhancing light penetration as well as potentially increasing nutrient fluxes. Some studies project that as the climate warms and sea ice further declines, primary production will continue to increase. Additional freshwater at the surface of the Arctic Ocean increases stratification and limits nutrient supply, which acts to reduce primary production. Therefore, these responses are likely to be spatially heterogeneous and dependent upon multiple confounding factors. At the top of the Arctic food chain, species such as polar bears, walruses, and seals that rely exclusively on sea ice for hunting, birthing, and rearing their young will be negatively affected by reduced ice cover. In contrast, summer migrant whale species may benefit from feeding in a more productive ocean during the longer ice-free season. Sea ice decline has also affected fauna on land, where delayed autumn sea ice formation is associated with reduced body mass in polar bear mothers and cubs. The ivory gull uses the pack ice edges for nesting and foraging, and their populations have declined dramatically, most likely due to sea ice changes. The trajectory of ecosystem productivity will determine how marine mammals and vertebrate fauna will fare in a future with declining sea ice.

Consistent with Arctic amplification, sea ice decline is associated with the strongest warming along the coastal land surfaces. Permafrost temperature increases are largest in the farthest north and coldest land areas of the Arctic. Consistent with land-surface warming, the largest relative change of tundra vegetation greening has occurred in regions contiguous to the largest sea ice decline. Vegetation greening and land-surface warming trends have weakened over the tundra since about 2000, suggesting possible impacts from changes in the large-scale atmospheric circulation, near-coastal cloudiness, snow cover, or other processes.

Sea ice decline has important implications for the biogeochemistry and atmospheric chemistry in the Arctic. It is currently unclear whether sea ice decline will strengthen or lower the terrestrial uptake of CO_2 in the Arctic. The oceanic uptake of CO_2 is expected to increase with sea ice decline, but numerous poorly understood processes occurring in the vicinity of the ice make it difficult to predict the future oceanic uptake with confidence. Increased uptake of CO_2 by the ocean, together with the addition of low alkalinity ice meltwater to the ocean surface, has exacerbated ocean acidification (50). Terrestrial methane emissions are expected to increase due to sea ice–induced warming, but the precise magnitude is yet to be determined. Meanwhile, marine methane sources are not expected to change dramatically in the near future, but the uncertainty is much higher than for the terrestrial sources. In springtime as the sun returns, salts from sea ice are converted to reactive halogen atoms. These reactive halogens reduce ozone in the lowest atmospheric layer and lead to MDEs. First-year sea ice provides a favorable environment for this chemistry, which could become more active as more of the Arctic consists of first-year ice. Advances in our understanding of Arctic greenhouse gases and atmospheric chemistry will be critical for understanding future climate change.

Many studies are confirming that the Arctic marine system is a highly nonlinear and complex system, wherein regime shifts, tipping points, system cascade, and surprise must be expected (134). Management based on the projections of linear trends is bound to fail. Amplification processes, some of which are discussed above, suggest that the Arctic is sensitive to external forcing, with substantial feedbacks to lower latitudes that may intensify with further declines in sea ice.

The Arctic therefore is not simply a passive casualty of climate change. Zhang et al. (135), for example, argue for a fundamental change in the high-latitude atmospheric circulation during the twenty-first century. Indeed, a changing Canada Basin feeds back on the global system, with potential impacts on ocean currents and global precipitation patterns. This two-way interaction is discussed by Overland et al. (136) and Francis & Vavrus (22). Global warming and Arctic amplification act to reduce the sea ice cover, freshen the surface layers, reduce albedo, and allow increased heat storage in the upper ocean (43). This enhanced heat storage in newly sea ice–free ocean areas is then returned to the atmosphere in the following autumn, thus modifying the large-scale wind field and the Polar Vortex. As noted by Overland et al. (136), observations from winter in 2009–2010 showed that the typical Polar Vortex was weakened over the central Arctic, resulting in enhanced meridional air mass exchange and record snow and low temperatures: a warm Arctic–cold continents pattern. We can expect substantial progress in the next decade on this topic of atmospheric impacts of sea ice relative to natural variability, as it has generated substantial interest in the climate community (27) and captured the public's attention.

Additional topics should be considered for future reviews as the underlying research advances. Coastal erosion has dire consequences for life and property, and recent work suggests that sea ice decline is correlated with increased wave heights in the Bering (137) and Beaufort Seas (138). Increased wave heights interact with thawing permafrost soils to make the coasts more vulnerable to erosion. A future review should also address the impact of sea ice decline on human activity, including such topics as increased traffic, resource extraction enterprises, subsistence lifestyles, and ecosystem services. Our knowledge of the Arctic is expanding rapidly, so there is hope that in the coming decades society will be prepared to face the challenges of a changing Arctic.

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