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Loss of Sea Ice in the Arctic*

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Annu. Rev. Mar. Sci. 2009. 1:417–41

First published online as a Review in Advance on October 22, 2008

The *Annual Review of Marine Science* is online at marine.annualreviews.org

This article's doi:
10.1146/annurev.marine.010908.163805

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1941-1405/09/0115-0417$20.00

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Key Words

Arctic sea ice, climate change, ice-albedo feedback

Abstract

The Arctic sea ice cover is in decline. The areal extent of the ice cover has been decreasing for the past few decades at an accelerating rate. Evidence also points to a decrease in sea ice thickness and a reduction in the amount of thicker perennial sea ice. A general global warming trend has made the ice cover more vulnerable to natural fluctuations in atmospheric and oceanic forcing. The observed reduction in Arctic sea ice is a consequence of both thermodynamic and dynamic processes, including such factors as preconditioning of the ice cover, overall warming trends, changes in cloud coverage, shifts in atmospheric circulation patterns, increased export of older ice out of the Arctic, advection of ocean heat from the Pacific and North Atlantic, enhanced solar heating of the ocean, and the ice-albedo feedback. The diminishing Arctic sea ice is creating social, political, economic, and ecological challenges.

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INTRODUCTION

"Ultimata Thule," farthest north. For centuries, those words denoted adventure and the unknown as explorers tried to reach the North Pole and tried to find a passageway across the top of the world. There were fantastic tales of what the Arctic might be like, including tropical islands and lost civilizations. The reality was even more exotic. The North Pole is a place so cold that the ocean froze, forming sea ice that could be as thin as a sheet of paper, or tens of meters thick. Sea ice could be so weak that a person would fall through to the ocean or so strong that it could crush a ship. Sea ice could appear massive and immobile and yet move tens of kilometers per day, driven by winds and currents. For the early explorers the Arctic sea ice cover was a mysterious material, but gradually over time our understanding of it grew through expeditions, such as Nansen's extraordinary drift on the Fram from 1893 to 1896. Knowledge about the Arctic Ocean continued to accrue with a long series of Russian drifting ice camps starting in the 1930s. The Arctic Ocean was of great interest and a research focus during the Cold War as a region where few surface ships could operate, but nuclear submarines could roam freely.

Over the years there have been many motivations for studying the Arctic sea ice cover, including research, exploration, military operations, and resource development. Today climate change provides a strong impetus. General circulation models (GCM) are a powerful tool for investigating climate change. Simulations from these models investigate the impact of different greenhouse gas forcing on the global climate system. **Figure 1** shows the Intergovernmental Panel on Climate Change Projection for the year 2090, which assumes a business-as-usual scenario (Solomon et al. 2007). The map is virtually all red, indicating widespread warming. The darkest red and magenta, where the warming is predicted to be greatest, is in the Arctic. In essence the Arctic acts as a harbinger of climate change.

The Arctic sea ice cover is a thin veneer of floating ice, on average less than a few meters thick, but millions of square kilometers in areal extent. In winter, temperatures are so cold that the ocean freezes and the ice grows thicker. Summer temperatures are near freezing and the ice melts, on both the surface and the bottom. The ice can drift up to tens of kilometers per day, driven mainly by winds and to a lesser extent by currents. The ice cover has a tremendous amount of variability

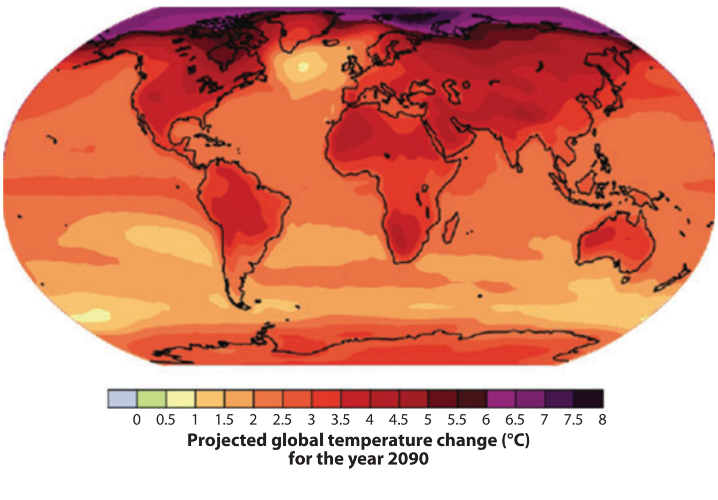

Figure 1

Business-as-usual projection of global temperature change for the year 2090 [Intergovernmental Panel on Climate Change (IPCC) report scenario 1B]. From the technical summary of the IPCC AR4 report (Solomon et al. 2007).

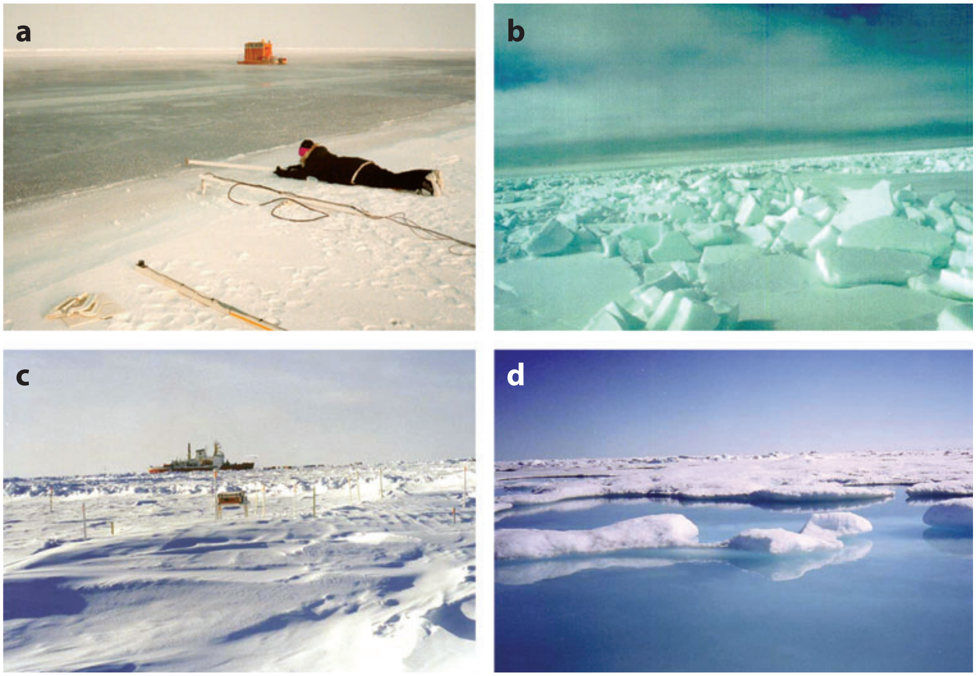

Figure 2

Photographs showing the stages of sea ice: (*a*) new ice only a few centimeters thick; (*b*) ridged seasonal ice, (*c*) perennial ice in April before melt; (*d*) and perennial ice in August during melt.

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(**Figure 2**). There is spatial variability both in the horizontal and in the vertical dimension. Over short horizontal distances of several meters the ice thicknesses can vary from open water to ridges tens of meters thick. There are temporal changes in the ice cover, most notably the annual cycle of freezing and melting. In much of the Arctic Ocean, eight to ten months of winter freezing alternate with two to four months of summer melt.

The sea ice cover is a grand integrator of heat. In a simplistic sense, an increase in heat input results in a decrease in the amount of sea ice; thus, observing the state and the amount of Arctic sea ice can provide a prime indicator of climate change.

OBSERVING SEA ICE CHANGE

Ice Extent

The ice extent is a key parameter in assessing the state of the ice cover and is expected to decrease in a warming climate. There is an excellent dataset to evaluate this because the extent of the Arctic sea ice cover has been monitored since the 1970s using satellite-based sensors. Passive microwave detectors, with their all-weather, day/night capability, can readily delineate between ice and ocean and have been effective in determining the extent of the ice cover (Parkinson et al. 1999).

There are large seasonal differences in ice extent. **Figure 3** maps the ice extent for March and September averaged over the period 1979 to 2000. The ice cover reaches its maximum extent in March at the end of winter and its minimum in September after summer melting. At its maximum, the entire Arctic Basin is ice covered and ice extends southward into the Bering Sea, the Sea of Ohkotsh, Hudson Bay, along the coasts of Greenland, and the Gulf of Bothnia, whereas in summer

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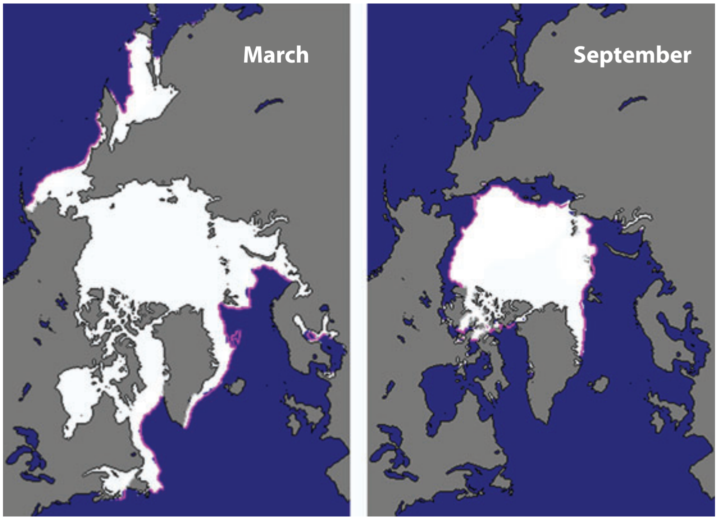

Figure 3

Sea ice extent averaged from 1979–2000 in March and September, when the ice cover is at its maximum and minimum extent, respectively. Figures from the Sea Ice Index courtesy of the National Snow and Ice Data Center (**http://www. nsidc.org/data/seaice_index**). The red lines indicate the 1979–2000 average ice extent for that month.

the ice retreats to the central Arctic plus a tongue of ice down the northwest coast of Greenland. The seasonal difference in these average extents is roughly a factor of two, with a maximum of 14 million km^2 and a minimum of 7 million km^2.

From a climate perspective, the interest is not in the seasonal cycle, but rather in the long-term trends. Monthly values of ice extent are plotted in **Figure 4**. The large annual oscillations

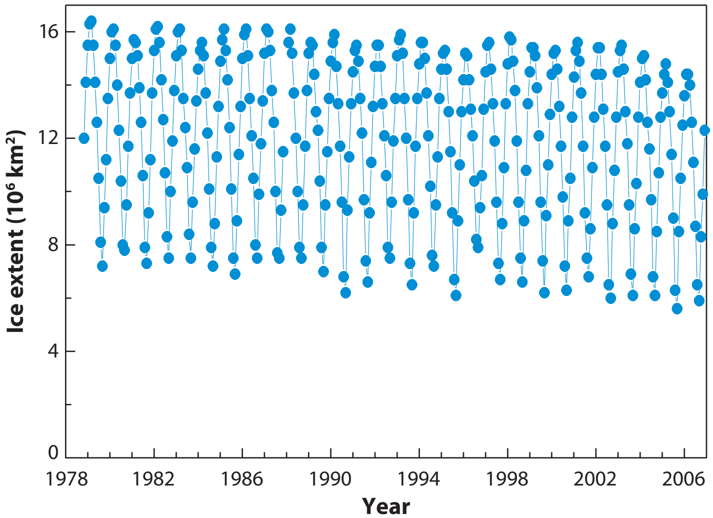

Figure 4

Time series of monthy ice extent derived from microwave satellite observations (Data courtesy of the National Snow and Ice Data Center).

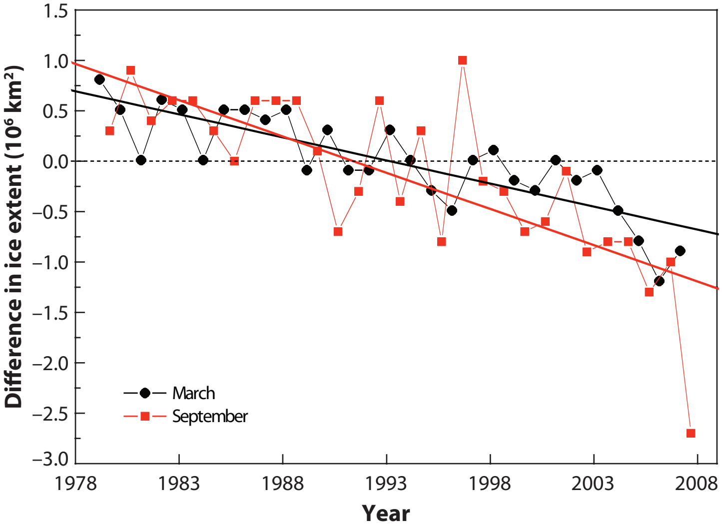

Figure 5

Time series of the anomalies in ice extent in March (the month of ice-extent maximum) and September (the month of ice-extent minimum) from the mean values for the time period 1979–2007. The rate of decrease for the March and September ice extents was 2.8% per decade and 11.3% per decade, respectively, based on a linear regression.

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again demonstrate the strength of the seasonal cycle and make it difficult to detect interannual variations and trends. To focus on trends, the time series of the anomaly in ice extent in March and September for the period 1979–2007 is provided in **Figure 5**. Here too a complicated signal is present with year-to-year fluctuations, such as the peak September ice extent occurring in 1996 after a minimum value in 1995. However, an overall downward trend is evident. For the past decade, ice extent anomalies have been negative. Also, for both months, a linear least squares fit of the data shows a negative trend with a rate of −2.8% per decade for March and −11.3% per decade for September relative to the 1979 values (Richter-Menge et al. 2007). September is a month of particular interest, because the ice is at its minimum extent and a climate change signal is potentially the greatest. The rate of decline of the summer sea ice cover has been accelerating in recent years. The rate of decline over the period 1979–2000 was −6.4% per decade (Comiso 2002, 2006), for 1979–2004 it was −7.7% per decade (Stroeve et al. 2005), and for 1979–2006 it was −8.4% per decade (Meier et al. 2007). Examining only the last decade of the September data, the decline is −18% per decade. A longer temporal perspective, including data derived from ship reports and aerial reconnaissance, indicates that the recent accelerated decline in the extent of the summer sea ice cover is unprecedented for at least a century (Walsh & Chapman 2001).

The most striking feature in **Figure 5** is the extreme record minimum ice extent of only 4.2 million km^2 set in September 2007. This value is 1.6 million km^2 (23%) less than the previous record set in September 2005 (Stroeve et al. 2008). **Figure 6** maps the spatial distribution of this decline in September ice extent from 1980 to 2005 to 2007. The total decrease from 1980 to 2007 was 3.6 million km^2, with the greatest ice retreat in the East Siberian, Chukchi, and Beaufort Seas. In addition, the Northwest Passage, in the western Arctic, was ice-free for part of the summer of 2007, and only a small portion of the Northern Sea Route in the eastern Arctic was ice covered.

Meier and coworkers (2007) further scrutinized trends in ice extent by performing the analysis on a regional basis. They divided the Arctic sea ice cover into eight distinct regions (**Figure 7**) and

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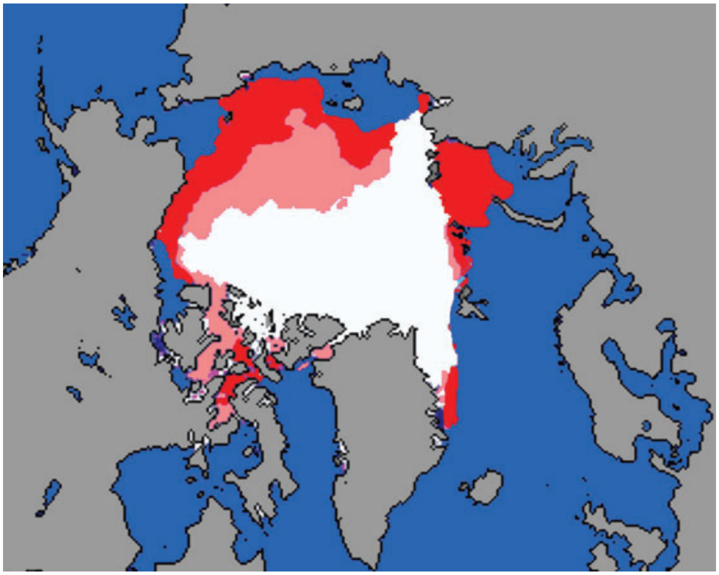

Figure 6

Comparison of September ice extent for 1980, 2005, and 2007, showing the 2007 ice extent (*white region*), the 2005 extent (*white region*), and the 1980 extent (*red*, *pink*, *and white regions*).

performed an analysis of the trends in ice extent for the period 1979–2006 for each month. The results are summarized in **Table 1**. Some regions (e.g., Central Arctic) have zero trends because they are completely ice covered during the year. In most cases, the trends are negative, indicating that the effects of warming are felt throughout the Arctic. The largest negative trends are found in summer in regions around the periphery of the Arctic Basin during months where melt is at or near its seasonal peak for a given region. These changes are due primarily to shifts in the onset of melt and freeze-up. When compared with the earlier work of Parkinson and colleagues (1999), which covered the period 1979–1996, most trends show an increase in rate of decline. This is further evidence that the rate of loss in the extent of the ice cover is widespread and has accelerated in recent years.

Comiso and coworkers (2008) examined changes in ice extent month by month over an annual cycle. They grouped results into five-year intervals starting with the period 1980–1984 (**Figure 8**). The smooth annual cycle of a maximum in early March and a minimum in September is evident in all the curves. Winter maxima were similar from 1980 to 1994, with smaller winter extents in subsequent periods. Results from 2000 through 2007 were consistently lower, in every month, than values from earlier years. Record minima were observed in 2005 during the winter and in 2007 from June through November. By March 2008, the ice extent had recovered from the September record minima and was 15 million km^2, comparable to typical maximum values. However, more of this ice extent is covered by ice formed since September 2007 and it is not known how its thickness compares to ice from earlier years. Indeed, ice thickness, as well as extent, defines the state of the ice cover, and must be considered.

Ice Thickness

Ice extent is the most readily observable parameter used to gauge the large-scale state of the ice cover, but it is only part of the story. The thickness of the ice is also important. As with ice extent, ice thickness also exhibits a strong seasonal signal. **Figure 9** shows the annual evolution of ice

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Figure 7

Regional divisions of the Arctic sea ice cover commonly used for regional analysis, with each region shown in a different color. The Baffin region (*teal blue*) includes the Labrador Sea and the Okhotsk region (*magenta*) includes the Sea of Japan. The Oceans region encompasses remaining ocean areas where small amounts of sea ice may exist, primarily in the Baltic Sea; gray areas represent land. From the *Annals of Glaciology* (Meier et al. 2007) with permission of the International Glaciological Society.

thickness and internal temperature for newly formed ice and for thick ice (Perovich & Elder 2002). The new ice started growing in late August and was approximately 0.4 m thick by mid-October. Ice thickness increased to 140 cm in June. The thin ice and 0.5-m-deep snow cover kept internal ice temperatures relatively warm during winter. This ice was so thin that it did not survive the summer melt season and completely melted by August. For the thick ice, growth started in late November when the effect of the cold autumn air temperatures finally propagated to the bottom of the ice. The average snow depth was 0.20 m and the ice growth was 0.75 m, with an increase from 1.85 m in October to 2.60 m in June. During summer, there was 0.80 m of melting on the surface of the ice and 0.30 m of melting on the bottom. The annual thickness ranges for these two cases were 150 cm to 0 cm and 2.60 m to 1.50 m.

To assess climate change impacts, the interest is not in individual points, but in a large-scale ice thickness dataset that spans several years. Unfortunately, at present there is no operational,

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Table 1 Regional trends for each month for the 1979–2006 time series. The units for the trends are percent per decade. Standard deviation values (in parentheses) are provided for the year trends and for all months of the total extent trend. A trend of zero generally reflects 100% ice cover in a region throughout the time series. Trends that are statistically significant at the 95% level are in italics and trends significant at the 99% level are in bold. Blank fields indicate months where little or no ice is found in the region. The Arctic Ocean is here the sum of the Laptev, East Siberian, Chukchi, Beaufort, and Arctic Ocean regions equivalent to the same region in Parkinson et al. (1999). From the *Annals of Glaciology* (Meier et al. 2007) with permission of the International Glaciological Society.

Month	Okhotsk	Bering	Hudson	St. Lawrence	Baffin	Greenland	Barenls	Canadian Archipelago	Kara	Laptev	East Siberian	Chukchi	Beaufort	Central Arctic	Arctic Ocean	Total
Jan.	**−11.8**	5.4	0.0	**−20.8**	**−9.0**	**−11.8**	**−12.7**	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**−3.3** **(0.4)**
Feb.	−7.9	2.0	0.0	*−7.9*	**−6.3**	**−11.7**	**−10.1**	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**−2.9** **(0.4)**
Mar.	−7.8	−4.8	0.0	−6.9	**−7.0**	**−10.6**	**−6.9**	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**−2.9** **(0.4)**
Apr.	**−14.3**	−1.8	0.0	−2.7	**−6.4**	**−9.3**	**−8.5**	0.0	−0.1	0.0	0.0	0.0	0.0	0.0	0.0	**−2.8** **(0.4)**
May	**−20.6**	−10.9	−0.1	−5.9	**−6.7**	**−6.0**	**−11.3**	−0.1	0.0	0.0	0.0	*−0.19*	0.0	0.0	0.0	**−2.6** **(0.6)**
June	−11.4	−7.8	−5.3		**−9.9**	**−5.8**	**−18.6**	**−1.3**	−0.9	*−1.1*	0.1	−4.3	−1.5	0.0	**−0.8**	**−3.1** **(0.4)**
July		−39.4	**−24.3**		**−16.9**	**−9.3**	**−24.1**	**−1.9**	**−11.6**	**−3.8**	−0.4	−6.7	−0.8	−0.1	**−1.2**	**−5.2** **(0.8)**
Aug.			**−22.9**		**−25.8**	**−16.0**	**−32.0**	**−3.8**	**−18.7**	**−11.6**	**−11.5**	**−15.4**	**−2.6**	**−0.5**	**−4.9**	**−7.0** **(1.2)**
Sept.			**−34.0**		−9.3	**−16.1**	−21.5	**−8.2**	−14.7	**−14.4**	**−17.2**	**−26.3**	**−9.6**	−0.5	**−7.4**	**−8.4** **(1.5)**
Oct.	**−22.0**	**−42.9**	**−46.6**		**−22.7**	**−8.3**	−12.7	**−2.2**	−2.9	−0.2	**−2.4**	**−18.6**	−2.3	−0.2	**−2.3**	**−4.0** **(0.8)**
Nov.	**−20.3**	*−20.3*	**−25.8**	3.4	**−11.5**	**−9.0**	*−8.6*	0.0	*−2.0*	0.0	0.0	**−8.0**	0.0	0.0	**−0.9**	**−4.0** **(0.7)**
Dec.	−4.6	3.0	−1.4	**−3.9**	−13.3	**−10.5**	**−13.8**	0.0	−0.2	0.0	0.0	0.0	0.0	0.1	0.0	**−2.6** **(0.5)**
Annual	−9.3 (4.2)	−1.9 (3.5)	−4.6 (1.1)	−5.9 (5.4)	**−9.0** **(2.7)**	**−9.8** **(2.7)**	**−11.3** **(3.8)**	**−1.2** **(0.5)**	**−2.8** **(1.3)**	**−1.8** **(1.0)**	**−2.1** **(0.8)**	**−4.9** **(1.1)**	*−1.2* *(0.9)*	*−0.1* *(0.1)*	**−1.3** **(0.3)**	**−3.6** **(0.4)**

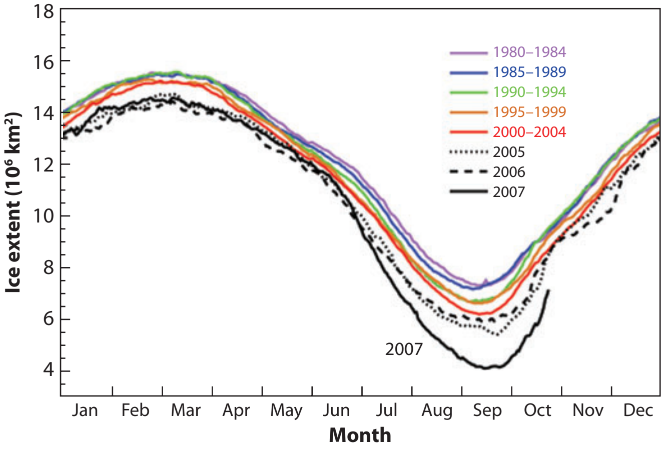

Figure 8

Daily ice extents averaged over the 5-year intervals 1980–1984 through 2000–2004 and for the years 2005, 2006, and 2007. Values are derived from satellite passive-microwave data. Adapted from Comiso et al. 2008.

routine method to determine large-scale sea ice thickness from space. Some promising technologies involve laser and radar altimeters (Laxon et al. 2003; Kwok et al. 2004, 2007), but they have only recently been introduced. Ice thickness measurements are often made during field campaigns (Tucker et al. 1987, 1999; Haas and Eicken 2001; Perovich et al. 2003; Haas 2004), either from the surface or from aircraft. However, these measurements cover only relatively small areas. Ice profiling sonars moored on the sea floor provide time series of ice thickness at individual locations.

The most comprehensive sets of ice thickness measurements available are those made by nuclear submarines that cruised under the Arctic ice pack from the 1950s to the present. The underside of the ice was mapped for operational purposes during these cruises. These ice bottom profiles were converted into ice thicknesses by assuming the ice was in isostatic equilibrium. The submarine ice thickness data do not deliver the Arctic-wide month-by-month coverage provided by the satellite

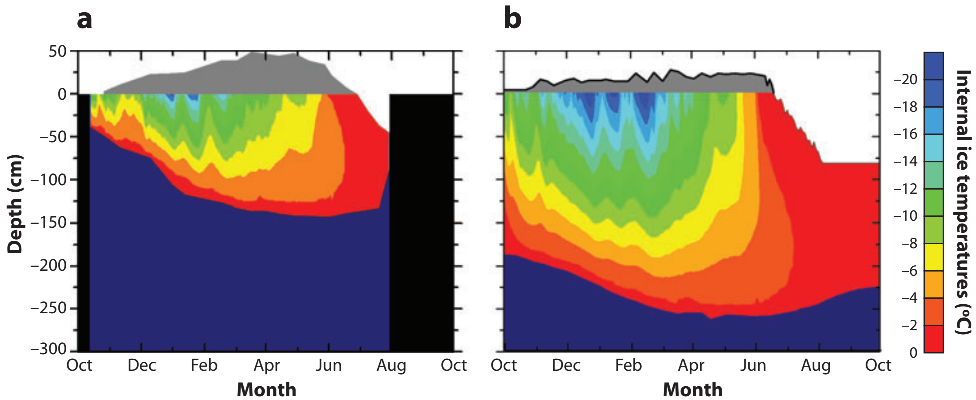

Figure 9

The annual cycle of ice mass balance and temperature for (*a*) seasonal ice and (*b*) perennial ice observed in the Beaufort Sea during 1997–1998. Internal ice temperatures range from −20°C (*blue*) to 0°C (*red*). The red–navy blue interface represents the bottom of the ice, the gray area represents the snow cover, and the black area represents missing data.

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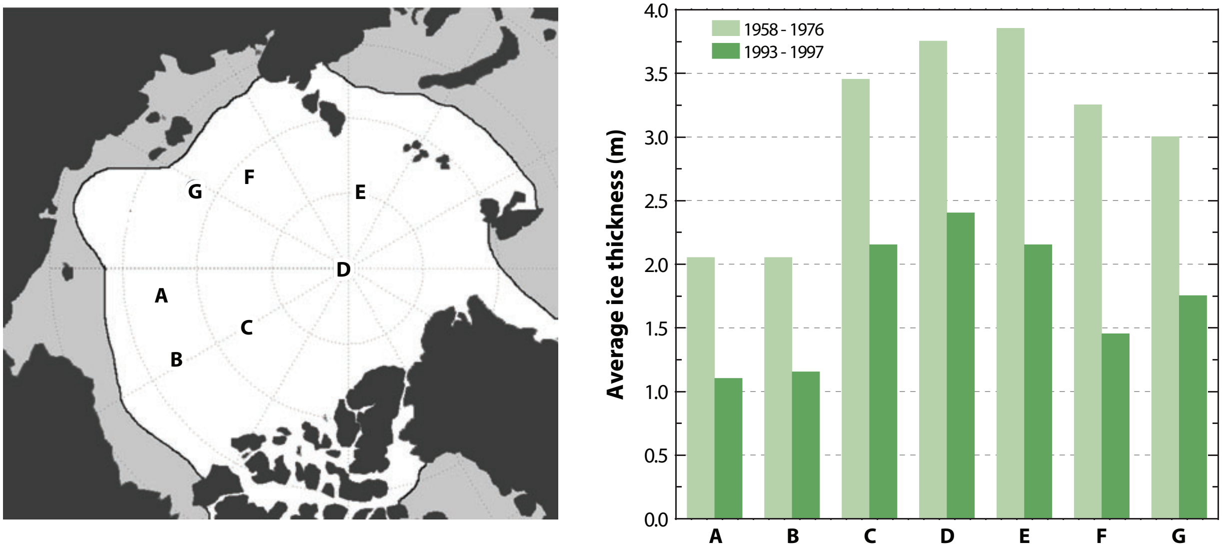

Figure 10

Changes in ice thickness as measured by submarines. Comparisons were made for seven different regions (*A-G in map*) and two time periods, 1958–1976 and 1993–1997. Results from Rothrock et al. (1999).

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record for ice extent. However, it is possible to combine these data to obtain insights into ice thickness changes. Rothrock and coworkers (1999) defined seven separate areas (**Figure 10*a***) and examined changes between two time periods: 1958 through 1976 and 1993 through 1997. The histogram in **Figure 10*b*** shows the average thickness for these areas and time periods. Substantial thinning in the 1990s data was evident at all seven locations and net decreases range from 1 m to 1.5 m. The overall decline averaged over the seven regions went from 3 m for 1958–1976 to less than 2 m for 1993–1997, a drop of 40%.

Seasonal and Perennial Sea Ice

Arctic sea ice can be divided into two basic age categories: seasonal ice and perennial ice. Seasonal ice has not yet survived a melt season, whereas perennial ice has endured at least one melt season. Perennial ice tends to be less saline and thicker than seasonal ice. Seasonal ice is found primarily around the periphery of the ice pack. The added thickness of perennial ice makes it more robust and less sensitive to changes in the thermodynamic and dynamic forcing. Therefore, the amount of perennial ice is also a measure of the health of the ice cover.

Kwok and coworkers (2004) investigated the annual cycle of perennial ice from 2000 through 2003 (**Figure 11**). The peak in perennial ice extent occurs in September at the end of the melt season; any ice that remains is then defined as perennial ice. Perennial ice extent decreases during winter as a result of the export of ice primarily through the Fram Strait. The decrease continues in summer as melting and export contribute to the decline. Finally, in September there is an increase in perennial ice extent, which occurs when the summer melt season ends and the first year ice that survived melt graduates and becomes multiyear ice. As **Figure 11** indicates, the shape of this annual cycle is similar from year to year, but there is interannual variability in the magnitude of the cycle. For example, in 2001 the September replenishment of perennial ice was approximately 1.4 million km^2, but in 2002 it was only 0.5 million km^2.

Seasonal sea ice: sea ice that has not survived a summer melt season

Perennial sea ice: sea ice that has survived a summer melt season

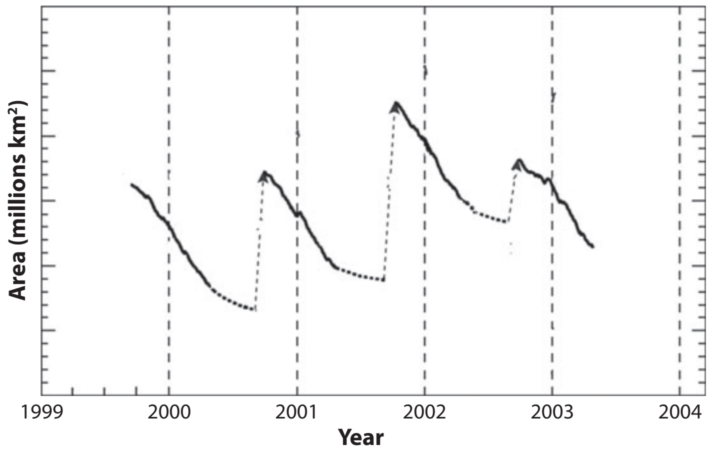

Figure 11

Annual cycle of perennial ice extent. Adapted from Kwok et al. (2004).

From a climate perspective, the interest is whether there is a trend in perennial ice extent. Nghiem et al. (2006, 2007) used data from the QuikSCAT/SeaWinds radar scatterometer along with ice age drift model results (Rigor and Wallace 2004) to investigate year-to-year changes in the perennial ice fraction in March during the past few decades (**Figure 12**). Interannual

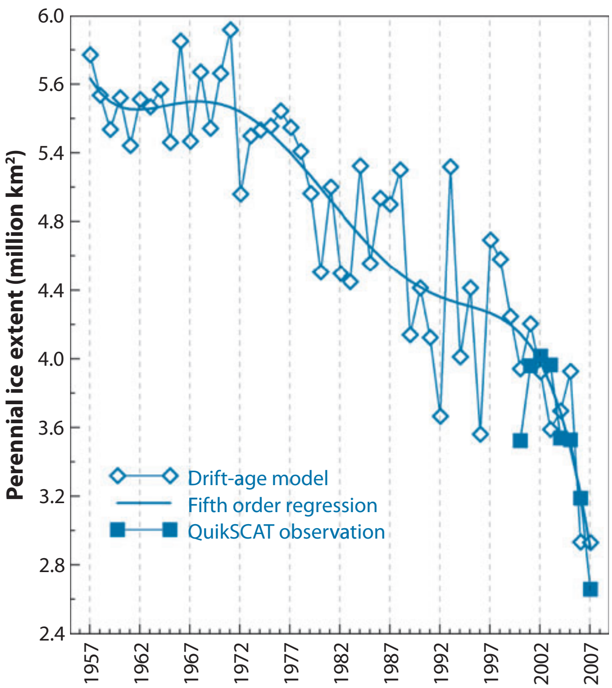

Figure 12

The perennial sea ice extent determined on March 21 from 1957–2007. Results are determined using a drift-age model (*open diamonds*) and observed by radar scatterometer (*solid squares*). Also plotted is a fifth order regression curve of the results. Adapted from Nghiem et al. 2007.

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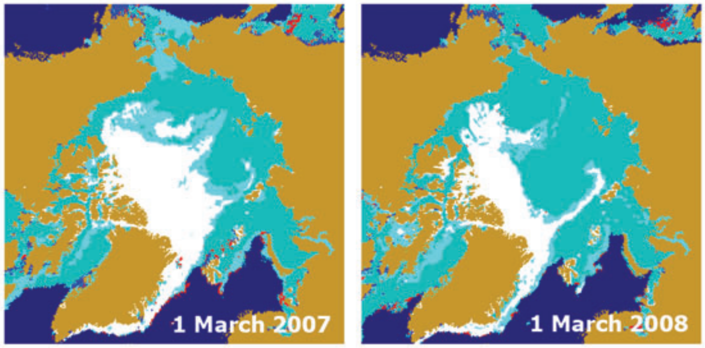

Figure 13

Maps of Arctic sea ice derived from QuikSCAT data for March 2007 and March 1, 2008, showing perennial sea ice (*white*), mixed ice (*aqua*), seasonal ice (*turquoise*), melt on ice surface (*red*), ice-free ocean (*blue*), and land (*brown*). Ice coverage was determined using QSCAT satellite results. Maps courtesy of S. Nghiem.

variability exists throughout the record, but a downward trend is evident beginning in the 1970s. This downward trend has accelerated significantly in the past few years. Overall, perennial ice decreased from 5.8 million km^2 in March 1957 to 2.6 million km^2 in March 2007. The spatial distribution of the decrease in perennial ice between March 2007 and 2008 is shown in **Figure 13**. The decrease of more than 1 million km^2 is striking. Perennial ice is almost exclusively in the western Arctic, with only a small amount in the eastern Arctic. The loss of perennial ice makes the ice cover more susceptible to future, rapid declines (Maslanik et al. 2007, Neumann 2007).

UNDERSTANDING THE OBSERVED CHANGES

Governing Mechanisms

Substantial reductions in the areal extent of the Arctic sea ice cover have been observed over the past few decades. Ice thicknesses in the central Arctic decreased in the 1990s (Rothrock et al. 1999). The next step is to understand these changes and to determine the causes and mechanisms that have driven these changes. The sea ice cover is not an isolated element, rather it is an integrated component of the Arctic system, with direct connections to the atmosphere and the ocean. Two distinct mechanisms govern the evolution of sea ice: thermodynamics and dynamics. Thermodynamics refers to the melting and freezing of the ice and dynamics refers to the motion of the ice. Changes in the ice cover should be interpreted in the context of thermodynamics and dynamics and from the perspective of interactions of the ice with the atmosphere and ocean.

Thermodynamics includes the sum of all the energy fluxes that affect the ice. If this sum is negative, the ice cools and grows. If the sum is positive, warming and melting occur. The surface heat budget of sea ice is illustrated in **Figure 14**. The surface heat budget consists of the radiative fluxes of solar radiation and longwave radiation and the turbulent fluxes of sensible and latent heat plus heat conduction through the ice. The radiative fluxes are the dominant terms (Persson et al. 2002), and solar radiation is greatly affected by the albedo (the fraction of the incident solar radiation that is reflected). The outgoing longwave radiation is a function of surface temperature and incoming longwave radiation is influenced by cloud cover. The turbulent fluxes depend on wind speed and the temperature and humidity differences between the atmosphere and the surface. At the ice bottom, the heat balance is simpler, consisting of heat conduction through the ice and a flux of heat from the ocean to the ice. The heat budget at both the surface and bottom of

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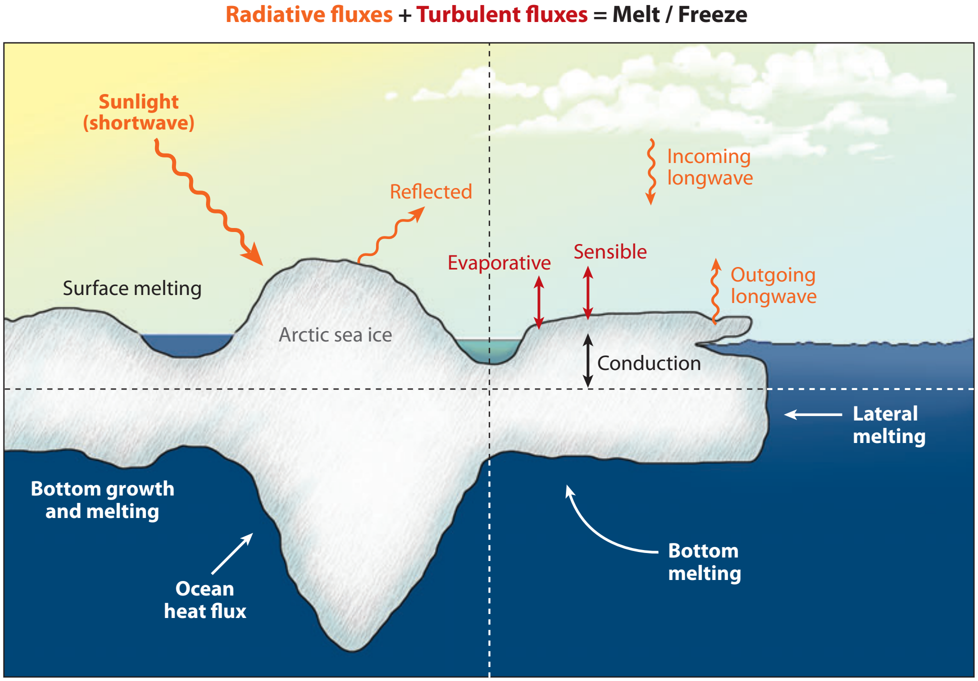

Figure 14

Schematic of the heat budget of sea ice. Arctic sea ice freezes on the bottom and can melt on the surface, bottom, or lateral edges of the ice and internally. Also shown is the equation for the surface heat budget. Radiative fluxes (*orange*) include net shortwave, incoming longwave, and outgoing longwave energy. The turbulent fluxes of sensible and evaporative heat are in red. The conductive energy transfer is in black.

the ice can vary on small spatial scales depending on snow depth, ice thickness, albedo, and ice topography.

Dynamics includes the motion of the ice and can cause rapid changes in the thickness of the ice. For example, divergence of the ice cover can result in open water, whereas convergence causes ridging and an increase in ice thickness. The acceleration of the ice cover depends on surface wind stress, bottom ocean stress, sea surface tilt, Coriolis force, and internal ice stress. Surface winds are the dominant driver of ice motion (**Figure 15**).

The causes of the observed decline in Arctic sea ice are a mystery with many suspects. Recent research has assessed possible causes of the dramatic loss and implications for the future trajectory of the Arctic sea ice cover (Serreze et al. 2007). Possible causes are found in the factors that influence dynamics and thermodynamics. These factors include overall warming trends (Johannessen et al. 2004), changes in cloud coverage (Francis and Hunter 2006), shifts in atmospheric circulation patterns (Rigor & Wallace 2004, Maslanik et al. 2007), increased export of older ice out of the Fram Strait (Nghiem et al. 2006, 2007), advection of ocean heat from the Pacific (Woodgate et al. 2006, Shimada et al. 2006) and North Atlantic (Polyakov et al. 2003, 2007), and enhanced solar heating of the ocean (Perovich et al. 2007a). We now examine these factors in more detail.

Albedo: the fraction of the incident solar energy that is reflected by a surface; ranges from 0 to 1

Dynamics: Ice Motion

Because winds are the primary driver of ice drift, the atmospheric pressure field impacts sea ice motion and export. An empirical orthogonal function analysis of the sea-level pressure field shows

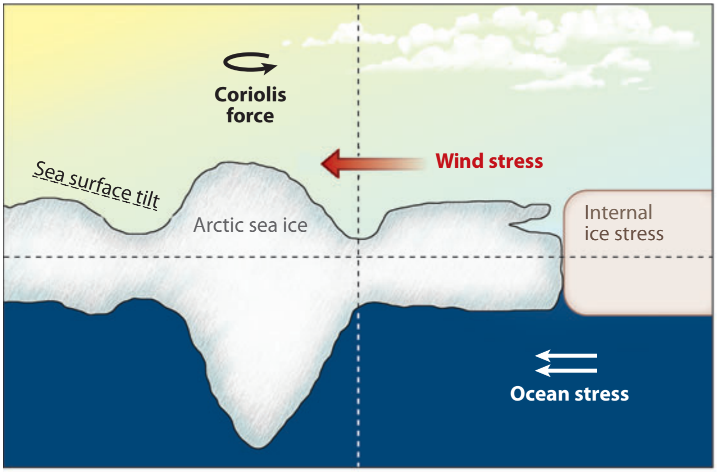

Figure 15

Schematic of the momentum balance of sea ice.

a mode of variability called the Arctic Oscillation (AO) (Thompson & Wallace 1998). The positive phase of the AO is associated with relative low pressure in the polar region and higher pressure at mid-latitudes, whereas the pattern is reversed for the negative phase. This change in pressure fields results in a change in the circulation pattern of the ice cover. The drift patterns for positive and negative AO are shown in **Figure 16**. The major difference is in the radius of the Beaufort Gyre and the track of the Transpolar Drift Stream. The Transpolar Drift Stream is the primary path to export ice out of the Arctic Basin. In contrast, the Beaufort Gyre is a circulation pattern that keeps ice in the basin, where it has an opportunity to grow thicker. For a positive AO the Beaufort Gyre is smaller, the Transpolar Drift Stream is straighter, and more ice is exported than for a negative AO (Rigor & Wallace 2004).

Rigor & Wallace (2004) examined the relationship between the AO index and the ice cover. The precise effect of the AO index on ice conditions depends on location and timescale. However, they found that in the winter of 1989–1990, the AO index was strongly positive and there was a massive export of perennial ice out of the Arctic Basin. Generally speaking, a positive AO reduced the

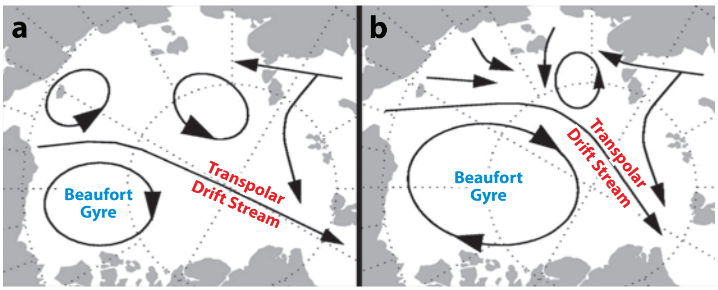

Figure 16

General drift pattern of Arctic sea ice for a (*a*) positive and (*b*) negative Arctic Oscillation. Drawing courtesy of Ignatius Rigor.

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amount of sea ice. They also found that greater than half of the variance in the summer ice extent was explained by the age of the ice. Kwok (2008) recently examined summer sea ice motion and determined that during the summers of 2006 and 2007, atmospheric pressure patterns enhanced the transport of sea ice from the Pacific to the Atlantic sector of the Arctic. This ice movement was responsible for 21% in 2006 and 15% in 2007 of the total ice loss in the Pacific sector.

There has been a general trend of increases in ice motion and ice export since the 1990s. Atmospheric circulation patterns have contributed to this increase. A key question is whether the thinning of the ice has changed the basic rheology of the ice cover, making it easier to move and resulting in more motion for a given wind forcing.

Thermodynamics: Heat Budget

The general warming trend of increased air temperatures over the Arctic Ocean has affected the sea ice cover by reducing ice growth and enhancing ice melt. Warming air temperatures impact the ice cover by increasing the duration of the melt season. Longer melt seasons result in more surface melting, with the date of melt onset of particular importance in terms of the total input of solar heat (Perovich et al. 2007b). Stroeve and colleagues (2006) used passive microwave imagery to assess the changes in Arctic sea ice melt season duration, start date, and end date. **Figure 17**

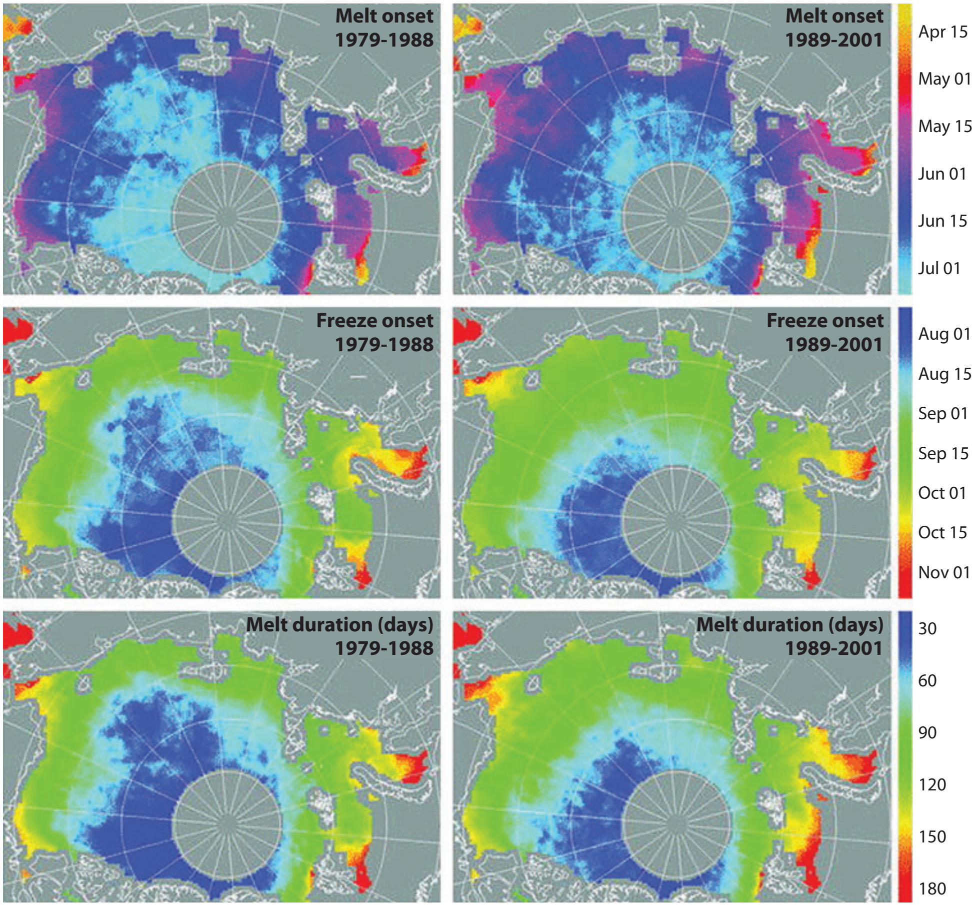

Figure 17

Contour maps comparing melt onset, freezeup onset, and melt season duration for two periods: 1979–1988 and 1989–2001. Adapted from the *Annals of Glaciology* (Stroeve et al. 2006) with permission of the International Glaciological Society.

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Table 2 Regional trends in the dates of melt onset and freeze-up and in the length of the melt season. The units for the trends are days per decade. Included are the values of the mean melt onset, freeze-up, and melt duration, with the standard deviation in parentheses. Trend values in bold are statistically significant at the 98% or higher confidence interval. From the *Annals of Glaciology* (Stroeve et al. 2006) with permission of the International Glaciological Society.

Region	Melt onset trend	Freeze-up trend	Duration of melt-season trend	Mean melt onset	Mean freeze-up	Mean melt-season duration
Central Arctic	**−3.9**	1.5	**5.4**	158.5 (5.9)	258.6 (6.6)	102.2 (9.8)
Beaufort	**−4.7**	4.9	**9.2**	142.3 (8.4)	276.0 (9.4)	132.5 (14.5)
Chukchi/East Siberian	**−4.6**	**6.9**	**11.8**	144.4 (8.3)	274.0 (7.6)	129.2 (13.6)
Laptev	−4.1	**5.3**	**9.7**	148.4 (9.8)	270.8 (8.5)	122.2 (16.5)
Kara	**−7.3**	**6.8**	**14.2**	142.7 (12.6)	296.3 (10.5)	153.2 (17.3)
Barents	**−8.8**	6.5	**16.9**	105.1 (11.6)	316.6 (17.4)	246.8 (17.5)

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compares data from the period from 1979–1988 with data from 1989–2001. Results of this work show a clear shift in the melt season duration, resulting from both earlier onset of melt and later freeze-up dates toward the end of the study period. Melt season trends are summarized in **Table 2**. These changes are most pronounced north of Alaska and Siberia, consistent with the results from Belchansky and coworkers (2004) and Perovich and coworkers (2007a). The rate of increase in the length of the melt season is greater than one week per decade, aside from the central Arctic, where it is 5.4 days per decade. Overall, the length of the melt season shows a strong correlation with the ice retreat observed in September north of Alaska and Siberia.

In summer, clouds affect the surface heat budget in a conflicting fashion by decreasing the solar radiation and increasing the incoming longwave radiation. Which of these influences dominates depends on the type of cloud cover present. Low clouds tend to warm the surface, whereas high ice clouds tend to cool the surface (Intrieri et al. 2002, Persson et al. 2002, Uttal et al. 2002). Francis & Hunter (2006) showed that the position of the summer ice edge is affected by springtime incoming longwave radiation as controlled by cloud cover and water vapor.

Heat stored in the ocean may also influence the ice cover. Polyakov and coworkers (2007) have followed warm temperature anomalies of Atlantic water that intruded into the Arctic Ocean through the Fram Strait at depths between 150 and 900 m and established that a large amount of heat is stored in this water mass. Warm inflows of Pacific water to the western Arctic Ocean through the Bering Sea (Shimada et al. 2006, Woodgate et al. 2006) have also been observed. The Pacific inflow is closer to the surface. The Arctic Ocean is highly stratified by strong vertical salinity gradients. River input and meltwater freshen the upper portion of the ocean, and advected heat must penetrate the stable layer at the underside of the ice.

Steele and coworkers (2008) report a pronounced increase in summertime warming of the upper ocean since the 1990s, with sea surface temperatures as high as 5°C observed in 2007. This upper ocean heat content is roughly equivalent to the amount of heat needed to melt/freeze 0.75 m of ice. Solar heating of the upper ocean is a possible source for the heat observed by Steele and coworkers (2008). Perovich and coworkers (2007a) took a synthetic approach to explore the input of solar heat directly into the ocean by combining field observations of ocean albedo, satellite-derived open water areas, and incident irradiances determined from meteorological models. The solar heat that is input directly to the ocean (F_{rw}) is equal to

$$F_{rw} = F_r(1 - \alpha)A_w,$$

where F_r is the incident solar irradiance, A_w is the fraction of the area covered by ocean, and α is the albedo. The albedo for the ocean is equal to 0.07 (Pegau & Paulson 2001). As the sea ice extent decreases, the solar heat input increases.

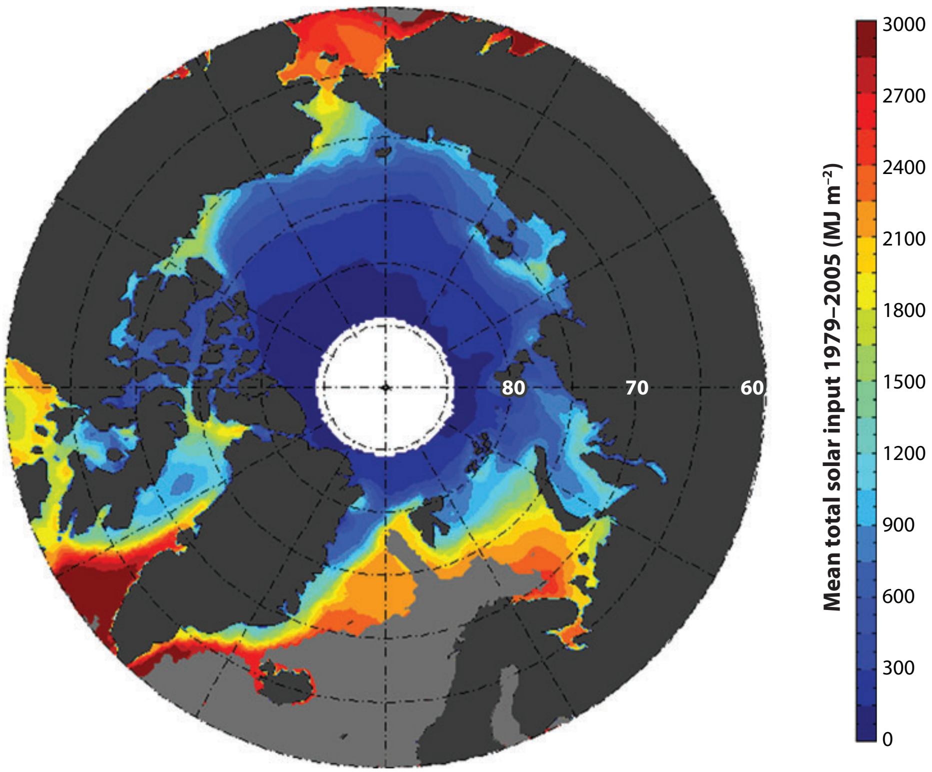

Figure 18

Map of mean total annual solar input for the years 1979–2005.

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The mean value of the annual solar heat input into the surface ocean was determined for 1979 to 2005 and is plotted in **Figure 18**. Values range from a few thousand MJ m^{-2} at lower latitudes in the seasonal ice zone to only a few hundred MJ m^{-2} at high latitudes in the perennial ice regime. It takes approximately 3 MJ m^{-2} to thin the ice by 0.01 m and there are other components to the heat budget in addition to the solar heat input. The largest values of solar input occur in the seasonal ice zone, where ice retreat commences in late spring or early summer. The solar heat input patterns at high latitude reflect the latitudinal dependence of incident irradiance, with a decreasing trend toward the Pole.

The trends in the annual amount of solar heat absorbed by the ocean from 1979 to 2005 are mapped in **Figure 19**. Positive trends are prevalent over much of the Arctic with peak values of 5% per year. Overall, 89% of the area has a positive trend of increasing solar heat input. There is a small region with a negative trend along the northern edge of the Canadian Archipelago, where ice motion caused increases in the amount of ice. Trends were modest in magnitude, with the median and mean trend for the entire study region equal to +0.64% yr^{-1} and +0.81% yr^{-1}, respectively. These values appear rather small: a few cm per year of ice thinning, less than one W m^{-2} of additional heat flux per year. However, the increase in heat input is cumulative and after a few decades, the total changes are considerable. For example, the solar heat input in the area of maximum increase more than doubled during the period of record. The increase in solar heating is significant because it may portend an amplification of change through the ice-albedo feedback.

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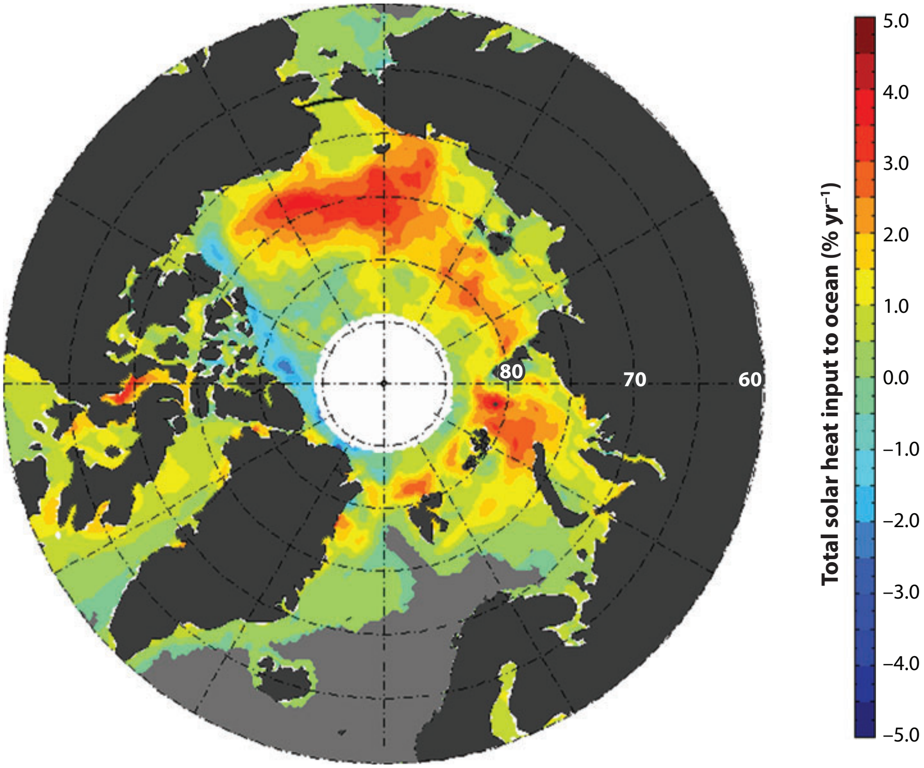

Figure 19

Map of the linear trend of annual total solar heat input directly to the ocean. Adapted from Perovich et al. (2007a).

Ice-Albedo Feedback

The Arctic sea ice cover is more than a harbinger of climate change, it may also be an amplifier of climate change through processes such as the ice-albedo feedback. Part of the importance of the Arctic sea ice cover in the global climate system is its central role in driving Northern Hemisphere ice-albedo feedback (Holland & Bitz 2003, Hall 2004). Model results from GCMs indicate that the ice-albedo feedback contributes to the polar amplification of climate change (Holland & Bitz 2003, Zhang & Walsh 2006).

The ice-albedo feedback is illustrated in part by **Figure 20**. Sea ice, when covered by snow, reflects up to 85% of the incident solar energy (Perovich et al. 2002). In contrast, the dark ocean reflects only 7% of the incident solar energy. The contrast in albedo is extreme; snow is the best natural reflector and the ocean is among the worst. The solar heat absorbed in the ocean results in melting and an increase in the area of open ocean, which in turn leads to more solar heat input and more melting and on and on. Albedo changes also occur during melt in the interior of the sea ice cover. **Figure 21** shows aerial photographs taken in April before the onset of melt and in August near the end of the melt season. Because of melting and divergence, the amount of open water is greater in August. Also, melting has reduced the overall albedo of the ice surface. The highly reflective snow (albedo = 0.85) has melted and now the surface consists of bare ice (albedo = 0.65) and melt ponds (albedo = 0.2 to 0.4). The melt ponds are the blue areas in **Figure 21**. Overall there is a decrease in the ice albedo compared with the premelt case in May. As the ice

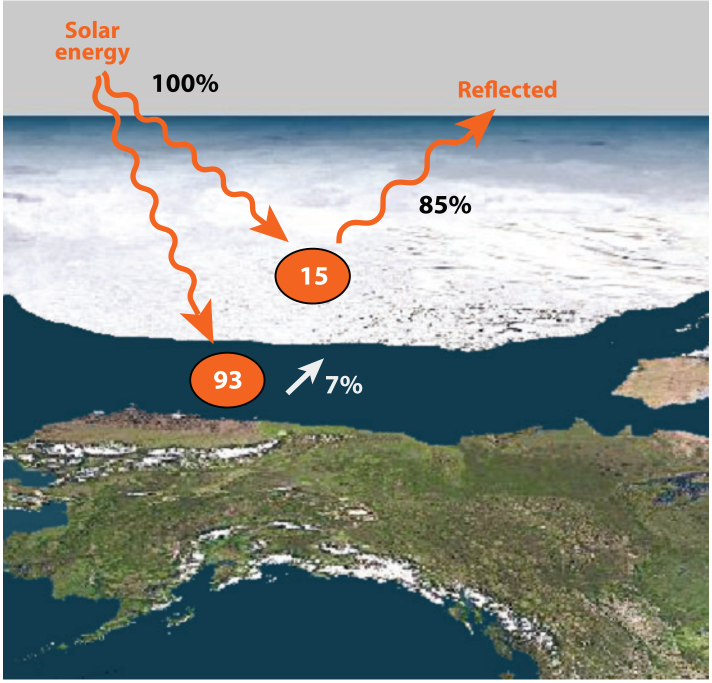

Figure 20

Differences in albedo between sea ice and the ocean that drive the ice-albedo feedback. The numbers in the orange circles denote the fraction of the incident solar energy that is absorbed and the numbers by the arrows denote the amount reflected.

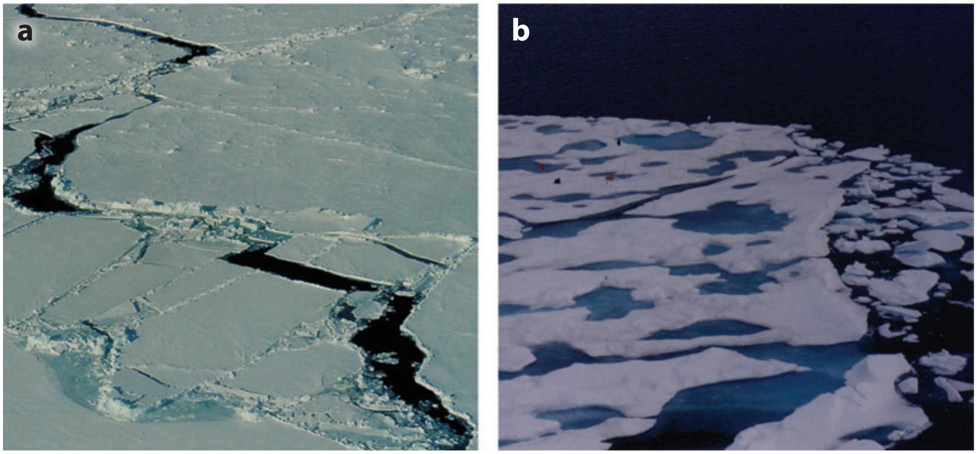

Figure 21

Aerial photographs of Arctic sea ice in (*a*) April and in (*b*) August. The blue areas in the August photograph are melt ponds, places where surface melt water collects.

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melts its albedo decreases, and more solar heat is absorbed, further enhancing melting. These two processes constitute the ice-albedo feedback, which is a positive feedback that can build upon itself and accelerate. Positive feedbacks are of great interest from a climate perspective because they can magnify small perturbations into large transformations. The ice-albedo feedback takes on added importance in the context of a thinner, smaller, more sensitive ice cover.

IPCC: Intergovernmental Panel on Climate Change

Summer of 2007

The decrease in ice extent observed in September 2007 was extraordinary. The ice extent reached a new record minimum of of 4.2 million km^2, breaking the previous record minimum of 5.8 million km^2 set in 2005 by 1.6 million km^2. The observed decline in Arctic sea ice extent is well established. The focus is now directed at applying observations and models to understand the causes of this large retreat of the ice cover and the implications for longer-term trends. Although the 2007 ice retreat is still a topic of ongoing research, a basic storyline is beginning to emerge. It is a story that involves preconditioning, contributions from both the atmosphere and ocean, and the ice-albedo feedback.

The scientific consensus is that the preconditioning of the ice cover played a significant role in the 2007 decline. Increased ice export due to atmospheric pressure patterns (e.g., positive Arctic Oscillation) reduced the amount of perennial ice. A gradual warming trend reduced ice extent and thickness. Years of decreased ice extent, ice thinning, and reduced perennial ice volume predisposed the ice cover to further losses. Together, these changes have made the ice cover more vulnerable to natural fluctuations in atmospheric and ocean forcing. In the summer of 2007 a confluence of factors confronted this weakened ice cover. An unusual atmospheric circulation that was extremely favorable to ice melt prevailed over the Arctic during the summer of 2007 (Stroeve et al. 2008, Overland et al. 2008). Persistent flow from the South brought warm temperatures that caused melting and a wind pattern that enhanced ice export. Reduced cloudiness and the consequent increase in downwelling radiation at the surface enhanced surface melting of the ice (Kay et al. 2008). The advection of upper ocean heat from the North Pacific increased the heat content of the upper ocean (Shimada et al. 2008). Ice melt and divergence in the East Siberian, Chukchi, and Beaufort Seas caused an increase in the area of open water and led to solar heating of the upper ocean (Steele et al. 2008) and enhanced melt on the bottom of the ice (Perovich et al. 2008), triggering the ice-albedo feedback. Both observations (Perovich et al. 2008) and models (Zhang et al. 2008) indicate that the ice-albedo feedback contributed to the rapid ice loss. Taken together, these factors explain the September 2007 record minimum ice extent and foreshadow potential losses in the future.

FUTURE CHANGES AND IMPACTS

There has been considerable discussion about the ultimate demise of the Arctic sea ice cover. "When will the Arctic be ice free?" and "Has the Arctic sea ice passed a tipping point?" are oft-asked questions (Lindsay & Zhang 2005). It is important to remember that this question relates only to the summer ice cover, not the winter ice cover. There are consistent projections for continued atmospheric warming in the Arctic and for a continued decline in Arctic sea ice (Meehl et al. 2007, Overland & Wang 2007). All the Intergovernmental Panel on Climate Change (IPCC) model projections indicate that there will be seasonal ice in the winter and that projected winter declines will be smaller than summer losses. For a no-mitigation scenario, some IPCC AR4 model projections lead to an ice-free summer Arctic Ocean by 2100. A seasonal ice cover is projected to persist throughout the 21st century.

Using a subset of the IPCC AR4 models, Overland & Wang (2007) examined projected regional changes and found evidence for a decline in summer sea ice area of greater than 40% by 2050 for

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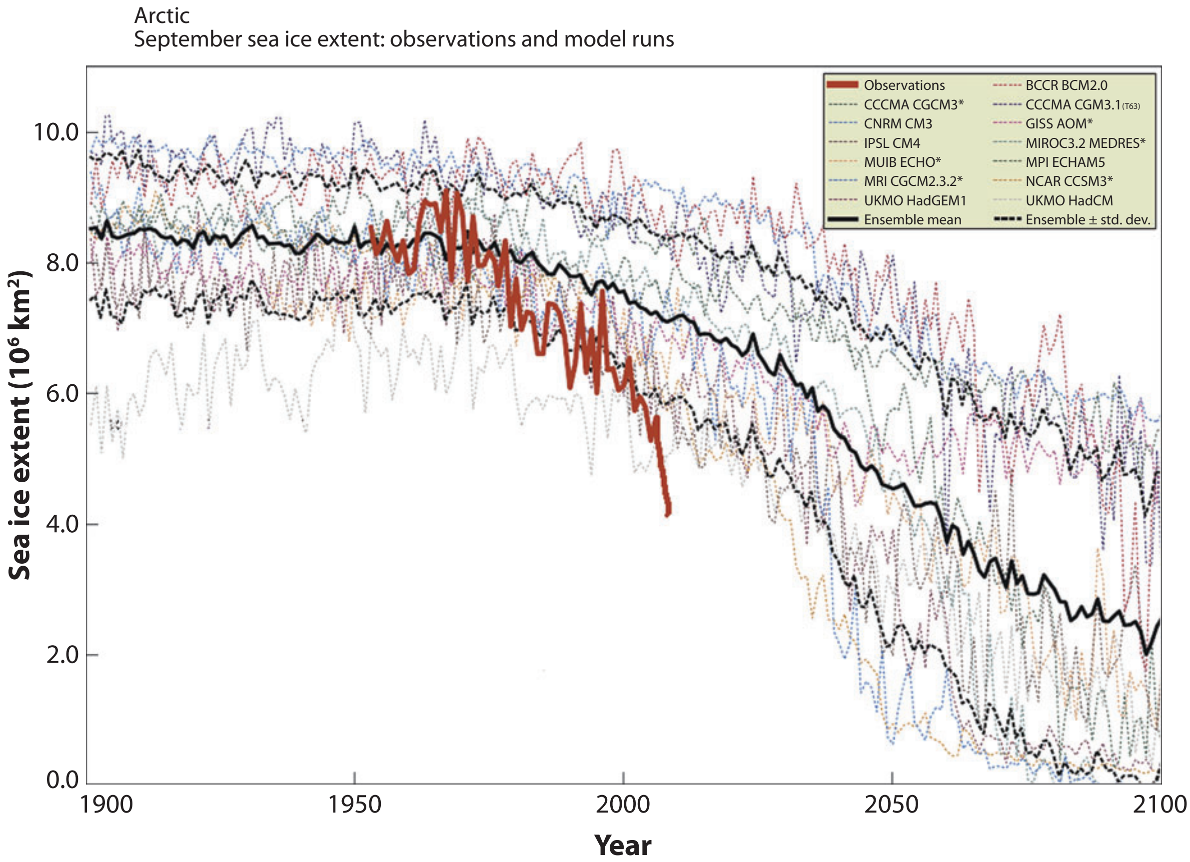

Figure 22

Time series of September Arctic sea ice extent determined using Intergovernmental Panel on Climate Change (IPCC) AR4 climate models. The model results are compared with observations (*solid red line*). The model ensemble mean is the solid black curve, with plus or minus one standard deviation shown by the dotted black curves. Adapted from Stroeve et al. (2007).

the marginal seas of the Arctic basin, including the East Siberian/Chukchi Sea and the Beaufort Sea. For the present-day seasonal ice zone, Overland & Wang (2007) find a winter sea ice area loss of 40% by 2050 for the Bering, Okhotsk, and Barents Seas. Little change is projected for the Baffin Bay/Labrador region compared with current conditions. Model uncertainty in the Kara/Laptev Seas and East Greenland seas was too great to make projections for these regions.

Stroeve and coworkers (2007) compared model projections of ice extent to observations (**Figure 22**). The results were striking. For the past decade, the observed September ice extent has been consistently below the model ensemble mean, and in the past several years has been more than a standard deviation below the mean. The 2007 observed September ice extent of only 4.1 million km^2 was roughly 50 years ahead of the ensemble mean forecast. This illustrates both the rapidity of the observed change and the difficulty of understanding and modeling all the factors involved in the change.

Perhaps the key question is not when the last fragment of summer ice will melt, but rather when will the decrease in the summer ice cover have an impact on the Arctic system and on human activities? It is having an impact now. The sea ice cover is not just part of a physical system, but also a biological, political, and economic system. Decreases in sea ice since 1998 have led

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to an increase in total phytoplankton production in the Arctic (Pabi et al. 2008), which could have profound implications for the structuring of marine ecosystems. The retreat of the ice cover has increased interest in shipping routes across the top of the world (Brigham & Ellis 2004). Both the Northern Sea Route and the Northwest Passage are being evaluated for their utility as standard shipping routes. The confluence of a retreating ice cover and increasing demands for natural resources, particularly petroleum, have sparked interest in explorations of the extensive continental shelves on the periphery of the Arctic Ocean. The uncertainty over exclusive economic zones raised by the Law of the Sea Treaty is complicating matters. The changes in the marine physical environment are generating changes in marine ecosystems (Grebmeier et al. 2006). The reduced ice cover is having deleterious effects on Arctic coastal communities. With sea ice forming later in the season, the coast is not only exposed to autumn storms, but also to storms with longer fetch. The subsequent coastal erosion has threatened some Arctic communities. The diminishing Arctic sea ice is creating social, political, economic, and ecological challenges.

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SUMMARY POINTS

1. There has been a significant decrease in the extent of Arctic sea ice, particularly at the end of summer.
2. There has been a decrease in the amount of perennial sea ice, making the ice cover more susceptible to changes in atmospheric and oceanic forcing.
3. The observed changes in sea ice are a result of thermodynamic and dynamic processes.
4. The observed September minimum annual ice extent has decreased faster than model predictions.
5. The ice-albedo feedback is contributing to the decline of the sea ice cover.

FUTURE ISSUES

1. Has the Arctic sea ice cover passed a tipping point and is it heading toward a new state?
2. What impact will a reduced summer ice cover have on the global climate system?
3. How can we better forecast and plan for future sea ice changes on regional, as well as Arctic, scales?
4. What are the societal implications for an ice-free summer Arctic Ocean?

DISCLOSURE STATEMENT

The authors are not aware of any potential biases that might be perceived as affecting the objectivity of this review.

ACKNOWLEDGMENTS

Support for the authors comes from the Arctic Program of the National Science Foundation, the Cryosphere Program at NASA, and the Arctic Research Office at the National Oceanic and Atmospheric Administration. The authors thank Chris Polashenski and Gioia Cattabriga for their helpful review of the manuscript.

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Annual Review of
Marine Science

Volume 1, 2009

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