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BY JOHN E. WALSH

# MELTING ICE

## What Is Happening to Arctic Sea Ice, and What Does It Mean for Us?

*The Roger Revelle Commemorative Lecture Series was created by the Ocean Studies Board of the National Academies in honor of Roger Revelle to highlight the important links between ocean sciences and public policy. John Walsh, the fourteenth annual lecturer, spoke on March 20, 2013, at the Baird Auditorium, Smithsonian Institution, National Museum of Natural History.*

ABSTRACT. Sea ice has emerged as the canary in the coal mine of climate change. Its summer extent in the Arctic has decreased by about 50% over the past decade, and the Arctic Ocean has undergone a regime shift from a cover of thick multiyear ice to a largely seasonal and much thinner ice cover. The recent loss is unprecedented in the periods of satellite and historical records of sea ice, and it also appears to be unique in paleo reconstructions spanning more than a thousand years. A "perfect storm" of warmer atmospheric and oceanic forcing, together with a boost from natural variability of wind forcing in some years, drove the change. However, the reduction of ice coverage is not apparent in some sub-Arctic regions during the winter, nor has it occurred in the Antarctic region.

Signals of a response to the loss of sea ice are emerging in the ocean and the atmosphere. Ocean heat storage during the ice-free season not only contributes to a later freeze-up than in the past, but it also reduces the thickness to which first-year ice can grow. The vulnerability of this thinner ice to rapid spring melt is a manifestation of the ice-albedo-temperature feedback that has long been postulated as a contributor to polar amplification of climate change. More notably for middle latitudes, the loss of sea ice appears to be triggering a reduction of the large-scale westerlies that characterize atmospheric circulation in middle and sub-polar latitudes. This response is consistent with increased persistence of departures from normal temperature, precipitation, and extreme weather during autumn and winter in heavily populated areas of the Northern Hemisphere.

### INTRODUCTION: IS THE ARCTIC A BELLWETHER OF GLOBAL CLIMATE CHANGE?

Over the past few decades, environmental changes in the Arctic have attracted the attention of scientists, residents of Arctic communities, policy and decision makers, and, more recently, the broader public. This region that was previously of little interest to outside residents has now become a focal point of concern about global climate change. It can be argued that the Arctic is now awakening the "sleeping giant" of public awareness of climate change and a growing acceptance of its reality.

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But what is driving the changes in the Arctic environment? And what are the consequences of these changes for regions outside the Arctic? While these questions are still at the core of ongoing research in many countries, some hints of the answers are emerging. Of all the variables that must be included in diagnostic studies of Arctic environmental change, sea ice is perhaps the most prominent. Sea ice plays a key role in climate by modifying the exchanges between the ocean and the atmosphere, but it also has many other complex connections to the climate system. It appears to respond to global influences, and recent decreases in sea ice may already be affecting the larger climate system through a variety of physical, dynamical, and ecological processes (AMAP, 2011). Moreover, sea ice is changing faster than other Arctic environmental variables. For these reasons, Arctic sea ice has been referred to as the "bellwether" of global climate change. Is such a notion justified? The answer to that question requires an understanding of the reasons for the recent dramatic changes in Arctic sea ice. The current understanding of those reasons is one focus of this article.

A second focus is the impact of retreating Arctic sea ice on the broader climate system, particularly in mid-latitudes. If sea ice truly provides an early indication of changes in global climate, then loss of sea ice could already be influencing climate in regions outside of the Arctic. There are scientific reasons to expect that such a mechanism exists, and modeling studies (Honda et al., 2009; Liu et al., 2012) and observational analyses (Francis and Vavrus, 2012) both provide some intriguing suggestions for effects on climate in the mid-latitudes. These effects, which may be quite consequential for heavily populated areas of Eurasia and the United States, can be counterintuitive, but are nevertheless scientifically plausible.

## CAUSES OF THE RECENT SEA ICE RETREAT

### What Is the Evidence for Sea Ice Retreat?

The most striking feature of recent changes in the Arctic, particularly in sea ice, is how quickly the Arctic is warming and ice is melting relative to changes seen in the long-term climate record. Figures 1 and 2 show reconstructions of Arctic summer temperatures (Kaufman et al., 2009) and Arctic sea ice (Kinnard et al., 2011) over time frames of the past 1,500–2,000 years. These reconstructions are based on proxy information—the history of past climate shifts preserved in ancient sediment deposits, in ice sheets, or in annual growth rings of trees. Natural systems change in response to environmental changes and hence "record" shifts in parameters such as temperature. The temperature reconstruction in Figure 1 is primarily from terrestrial sources, including lake sediments, pollen records, diatoms, and tree rings, which provide information on warm-season temperatures. It shows slow (summer) cooling in the Arctic for most of the past 2,000 years. This cooling is consistent with known slow variations in Earth-sun orbital parameters that affect the solar radiation reaching the Arctic in the sunlit portion of the year. However, the recent warming since the 1800s, confirmed by direct temperature measurements (red line in Figure 1), has left the Arctic warmer than at any time in the preceding 2,000 years by a considerable margin. The recent instrumental temperatures are outside the envelope of the natural variability seen in the reconstruction; for example, the warming is far more than simply a recovery from the so-called Little Ice Age, which is apparent from the late 1500s through the 1800s in Figure 1. The sea ice reconstruction in Figure 2 is based on high-resolution terrestrial proxies from the circum-Arctic

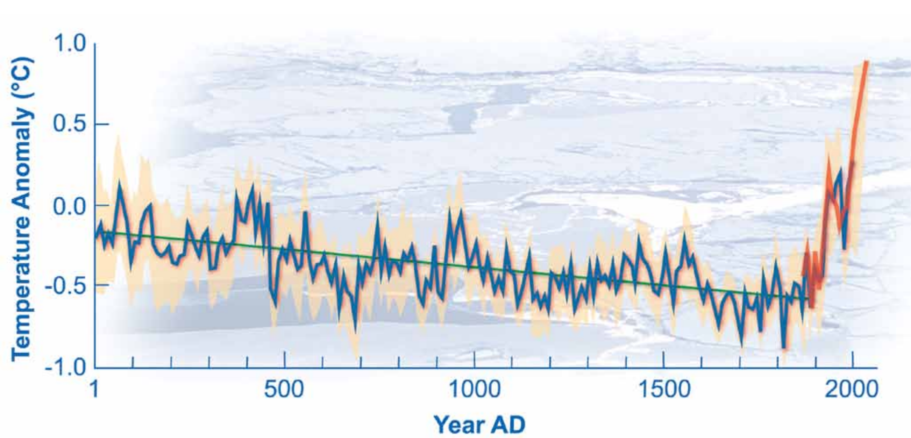



Figure 1. A reconstruction of Arctic summer temperatures. The blue line shows estimates of Arctic temperatures over the last 2,000 years, based on proxy records from lake sediments, ice cores, and tree rings. The green line shows the long-term cooling trend. The red line shows the recent warming based on actual observations. *From Kaufman et al. (2009), modified by UCAR*

domain: ice cores, tree rings, and lake sediments. As with the temperature reconstruction described above, these proxies respond primarily to changes in the warm season, so the reconstructions in Figure 2 depict summer sea ice variations. The pan-Arctic time series (red line) shows that the recent decline of sea ice is unprecedented in the 1,450-year reconstruction, and mirrors the recent, rapid warming evident in Figure 1. The abrupt decline in the Fram Strait region during the past several decades is also unique in the 1,450-year time series for that region. However, the reconstructions for the Chukchi Sea in Figure 2, and also for the Barents Sea (not shown), indicate that sea ice coverage in these regions was comparable to the present during the late 1500s and early 1600s. This tendency for smaller regions to show greater variability and behave differently from hemispheric averages is typical of variations in many climate variables (IPCC, 2007).

## Why Is the Arctic Warming So Quickly?

Figure 3 shows the geographic variation in the recent unprecedented rise in Arctic temperature. Over the past 60 years, the Arctic has warmed by more than 2°C, more than double the global average warming over the same period. Figure 3 illustrates the poleward increase, or "polar amplification," of this warming. Polar amplification is also seen in periods of cooling in the historical record, and it is attributable in part to the role of sea ice and its overlying snow cover (Serreze and Francis, 2006; Serreze et al., 2009). Specifically, there is a positive feedback that amplifies both warming and cooling trends because of the change in the amount of solar radiation reflected by sea ice. When sea ice melts, the darker water surface absorbs more of the sun's energy as heat, resulting in further warming and melting of ice and snow. Conversely, an expansion of sea ice results in greater reflection of solar radiation and reduces the amount of heat absorbed. This positive feedback phenomenon is called the temperature-ice-albedo coupling. Two other factors that appear to have contributed to the recent polar amplification of warming include an increase of atmospheric water vapor (a strong greenhouse gas) in the Arctic (Serreze et al., 2012) and an increase of poleward transports of heat by the ocean and the atmosphere (Shimada et al., 2006; Beszczynska-Möller et al., 2011).

Paired mid-September satellite images from 1992 and 2012 show the dramatic loss of sea ice in recent decades (Figure 4). The maximum seasonal retreat of sea ice usually occurs in mid-September, so these images capture

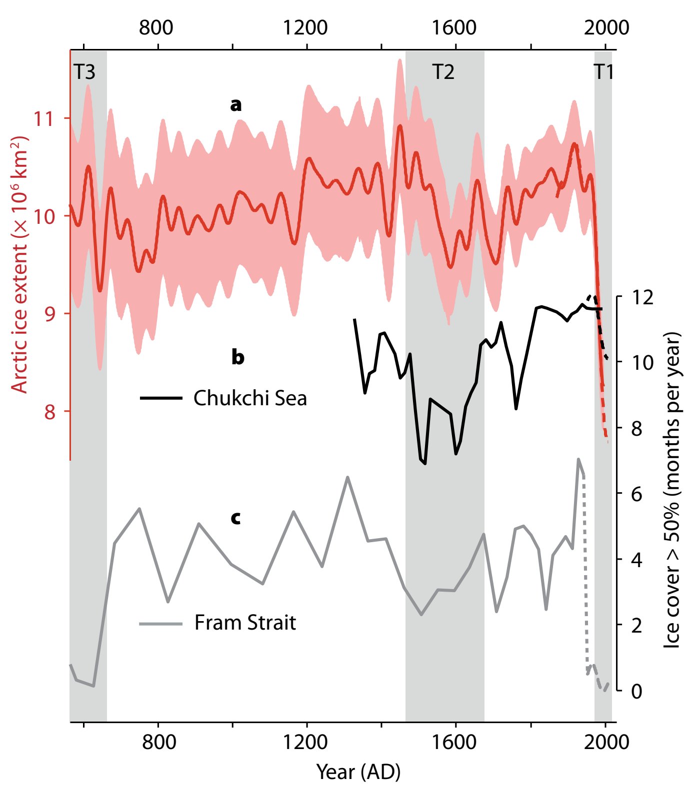



Figure 2. Reconstruction of Arctic summer sea ice variation. (a) Forty-year smoothed reconstructed late-summer Arctic sea ice extent, with 95% confidence interval, and yearly ice duration in the (b) Chukchi Sea and (c) Fram Strait. *Reprinted by permission from Macmillan Publishers Ltd.:* Nature, *Kinnard et al. (2011), copyright 2011*

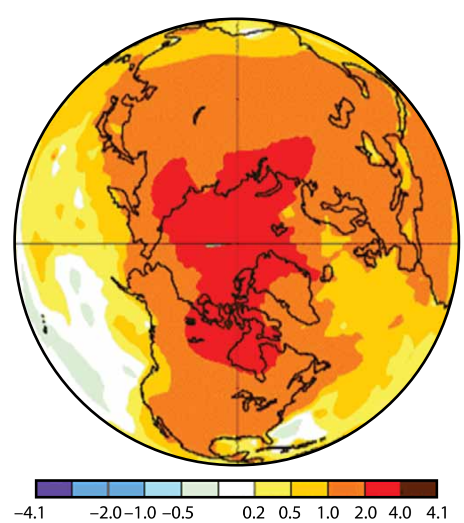



Figure 3. Geographic variation in the recent unprecedented rise in Arctic temperature. The figure illustrates the poleward increase, or "polar amplification," of warming. *Courtesy of NASA GISS*

the ice cover that survived the summer melt and hence can undergo additional growth in thickness during the following winter. The extent of sea ice in September 2012 was approximately half of the extent in 1992. The rapidity of this decrease is unprecedented with respect to the paleo-reconstruction shown in Figure 2, as well as other reconstructions based on additional types of sea ice information such as ship reports and coastal observations. Within the period of satellite observations (1979–2012), the loss of sea ice has occurred most abruptly in 2007 and 2012 (Perovich et al., 2013). In both of these years, the summer minimum was more than a half million square kilometers below the previous record. Interestingly, the extent of winter sea ice shows a much smaller decline in recent decades. The result is a much greater area of seasonal ice (i.e., ice that forms during the autumn/winter and melts the following spring). Because this ice has only a few months to grow, it is thin and readily deformed by the wind—a force that is responsible for much of the short-term ice movement.

## What Has Caused the Dramatic Loss of Ice in Recent Decades?

Warming of the Arctic has undoubtedly contributed to the loss of sea ice, but higher air temperatures alone cannot explain the rapid decrease over the past few decades (Stroeve et al., 2011). Other factors include:

- Periods of increased wind-driven transport of older, thicker ice from the Arctic into the North Atlantic
- Increased flow of warmer ocean waters into the Arctic from the North Atlantic and the North Pacific
- Increased atmospheric warming as a consequence of increased humidity in the Arctic, and perhaps also because of variations of cloudiness
- The amplified loss of sea ice due to increased absorption of solar radiation by the darker ocean surface, as described earlier

It is difficult to rank the relative importance of each of these driving forces, but the emerging consensus is that together they have resulted in the "perfect storm" of forcing responsible for the rapid sea ice loss. I next highlight the evidence for several of these drivers of Arctic sea ice loss.

The mean pattern of currents in the upper ocean of the Arctic and the subpolar regions includes warm, saline water from the North Atlantic that enters the Arctic Ocean through the Barents Sea and Fram Strait, then descends to depths of 100–400 m and circulates in a generally counterclockwise direction around the Arctic Ocean. This water transports heat acquired at lower latitudes to the Arctic. Some of this warmer water reaches the base of the sea ice and contributes to bottom melt. Measurements from ocean moorings and research vessels show that the inflowing Atlantic water has gotten warmer, albeit irregularly, over the past two decades (Alexeev et al., 2013), as can be seen in Figure 5. This warming has been detected not only where the Atlantic water flows in, but also along the continental shelf break north of the Siberian coast (Polyakov et al., 2010). The mechanisms by which heat is transferred from the deeper Atlantic waters to the surface is unclear, but double diffusion and mesoscale (~ 10 km diameter) eddies have been suggested as possible mechanisms. Double diffusion refers to the ability of heat to move more readily than salt through seawater, while eddies can move water and heat vertically. By using a heat budget approach, scientists have estimated that the warmer Atlantic water can account for around several tenths to a meter of bottom melt over the past decade.

On the Pacific side, Bering Strait is the entry corridor for warmer water of sub-Arctic origin. After entering the Chukchi Sea, this water generally moves eastward offshore of the northern

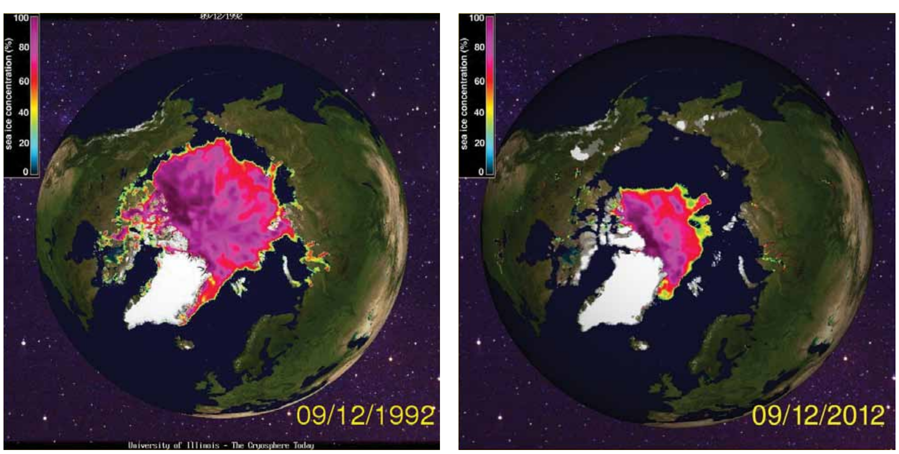



Figure 4. A pair of mid-September satellite images from 1992 and 2012 shows the dramatic loss of sea ice in recent decades. *Courtesy of University of Illinois, The Cryosphere Today*

Alaskan coast. There are indications of positive feedback whereby heat entering from the Pacific reduces the thickness and coverage of sea ice north of Alaska (Shimada et al., 2006). This thinner, looser ice is more mobile and susceptible to movement by winds that drive the Beaufort Gyre, thereby facilitating the transport of the warmer Pacific water from the Alaskan shelf to the deeper waters offshore. This transport leads to a reduction of the ice cover farther offshore, and the reduction then may be further enhanced by the albedo effect of reduced reflection of solar radiation. This mechanism is especially relevant to the ice loss of the past decade because the sector containing the Beaufort, Chukchi, and East Siberian Seas has experienced the greatest sea ice loss (Figure 4).

Recent heat budget studies have attempted to place the ice-albedo feedback into a quantitative framework (e.g., Perovich and Richter-Menge, 2009). The trend in the solar heat input to the Arctic Ocean over 1979–2005 exceeds 2% per year in certain areas, including the Beaufort-Chukchi-East Siberian Sea sector noted above, suggesting a 50% increase over the 26-year period. This increase precedes the rapid acceleration of ice retreat that began in 2007, so the percent increase would be even higher if evaluated through 2012. The increasing heat input, even prior to 2007, is far greater than the 1 to 2 W $m^{-2}$ of surface radiative warming from the increase in greenhouse gases. The more than 50% increase in solar absorption demonstrates the importance of the temperature-ice-albedo feedback in accelerating Arctic warming.

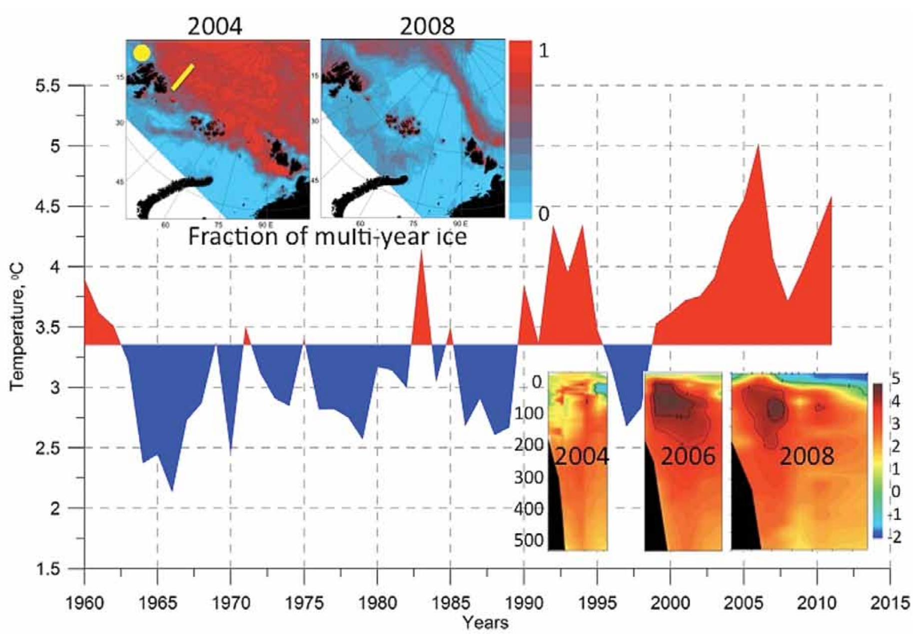



Figure 5. Measurements show that inflowing Atlantic water has gotten warmer over the past two decades. This image shows concentration of multiyear ice in 2004 and 2008 (two upper insets) and temperature in the Atlantic water core (main graph) measured in Fram Strait (yellow circle, upper left inset) and from transects of different extent (three lower insets) made in September 2004 and 2006 and October 2008 at 31°E, 80°N (location marked by yellow line in the upper left inset). *From Alexeev et al. (2013)*

## IMPACTS OF SEA ICE LOSS

The most direct and obvious impacts to date are in the Arctic, where sea ice loss is affecting people, marine life, and Arctic climate. However, there are emerging signs of impacts that extend into the mid-latitudes. Here, I highlight both local and distant impacts, beginning with the Arctic and then addressing impacts on other regions. The discussion is limited to impacts of diminished sea ice, acknowledging that Arctic warming also has other important impacts such as the contribution of melting glaciers and ice sheets to rising sea level.

### How Does Sea Ice Loss Impact People in the Arctic?

Coastal communities in Alaska and Siberia are experiencing increased flooding and coastal erosion as a result of the loss of the sea ice buffer that previously protected the coast from wind-driven waves during summer and autumn storms. As a result, several communities in Alaska are facing costly relocation away from the coast. An increase in ship traffic is another impact of the retreating sea ice cover, as the lengthening open-water season presents opportunities for offshore resource extraction, tourism, and shortened transit times for the marine transport industry. The oil and gas industry is a particular beneficiary of the diminished ice cover, as seen by the recent increase in exploratory activity over the shelf seas north of Alaska and Russia. Such activity brings potential benefits as well as risks to northern communities.

## How Does Rapid Loss of Arctic Sea Ice Impact Marine Life?

In the Bering Sea, there is some evidence that individual species as well as ecosystems respond to climate variations (Grebmeier et al., 2006). But farther north, in the Arctic Ocean, the dynamics of ecosystems and the food web are much less known. This lack of knowledge is reflected in the decision of the federal government to impose a moratorium on commercial fishing in US waters north of Bering Strait. The US Department of the Interior has listed the polar bear as a threatened species, based in part on changes in polar bear habitat arising from sea ice retreat (Figure 6).

Assessments of changing sea ice impacts on marine life, particularly the lower trophic levels, are largely reliant on modeling studies. Marine ecosystem modeling is a key element of the US-supported Bering Sea Ecosystem Study (BEST), and biogeochemical modeling is just now being applied to the Arctic Ocean, where the magnitude of sea ice retreat is greatest. One such modeling study incorporated marine biogeochemical cycling into a state-of-the-art Arctic Ocean sea ice model (Zhang et al., 2010). Tested by simulating a two-decade period in the recent past (a “hindcast”), the model successfully reproduced the observed levels of sea ice loss and also showed increases in primary productivity (photosynthesis by algae and plankton at the base of the food web) consistent with satellite-derived estimates. The simulated primary productivity increased at various depths in the water column, including areas under sea ice. The under-ice increases are consistent with the greater penetration of light when ice is thinner. In the model, diatoms and flagellates increased, as well as two types of zooplankton. Although the simulations do not extend to the most recent years of greatest sea ice retreat, the increased productivity of lower trophic levels has profound implications for higher trophic levels in the food web, including fish and marine mammals, with the potential to alter the ecological structure of large areas of the Arctic Ocean that have historically been covered by perennial sea ice.

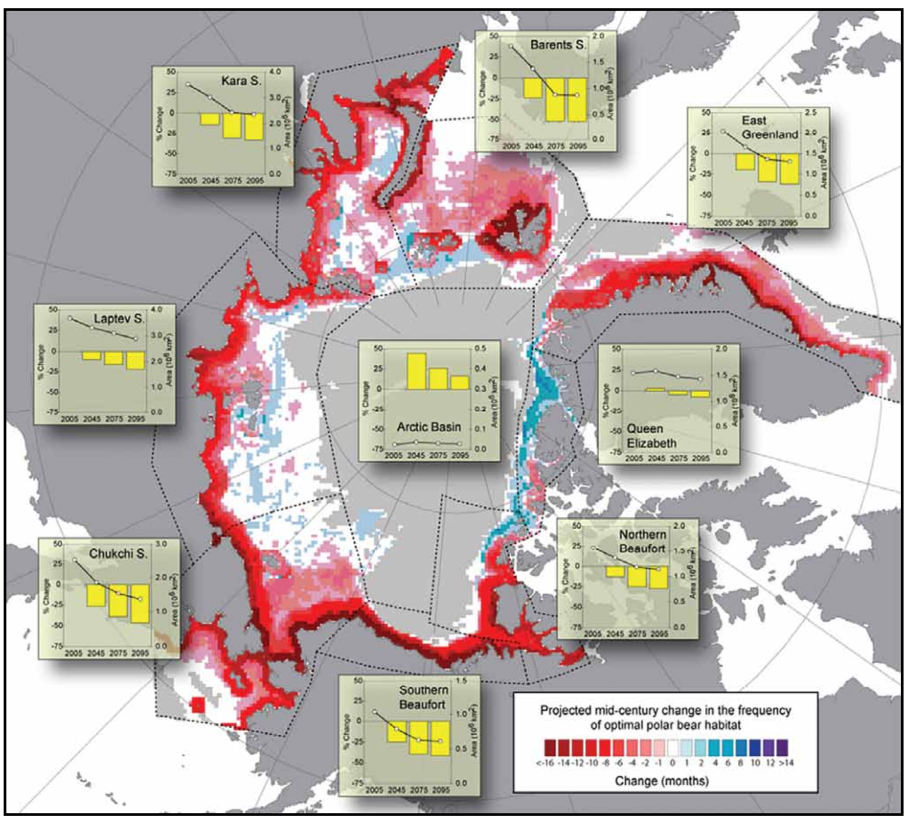



Figure 6. Projected changes in spatial distribution and integrated annual area of optimal polar bear habitat. The base map shows the cumulative number of months per decade where optimal polar bear habitat is either lost (red) or gained (blue) from 2001–2010 to 2041–2050. Offshore gray shading denotes areas where optimal habitat is absent in both periods. Insets show the average annual cumulative area of optimal habitat (right y-axis, line plot) for four 10-year periods in the twenty-first century (x-axis midpoints) and their associated percent change in area (left y-axis, histograms) relative to the first decade (2001–2010). *Courtesy of USGS*

## What Are the Impacts of Rapid Loss of Arctic Sea Ice on Climate Change?

The continental shelves of the Russian seas are among the largest in the world, and much of the seafloor in these seas contains relict permafrost. This permafrost and the underlying layers contain large stores of methane, a powerful greenhouse gas, in the form of methane hydrates. Recent measurements from these areas (Shakhova et al., 2010) have detected releases of methane (methane flares) consistent with perforations in the permafrost above the hydrate stores (Figure 7). The extent to which warming of the shelf waters, enhanced by sea ice retreat in this region, has accelerated the subsea permafrost thaw and the release of the methane stores is not known. However, preliminary estimates suggest that the amount of methane being released from the East Siberian Shelf region may be comparable to the amount released from the remainder of the global ocean. Given the plausibility of further acceleration of subsea permafrost thaw in areas of sea ice loss, together with the potency of methane as a greenhouse gas, this region bears watching for its potential to contribute to future global warming.

The most direct impact of sea ice retreat on climate is the warming of the Arctic atmosphere. The warming would be expected to be strongest in autumn, when the additional heat absorbed by the newly open ocean delays freeze-up and is released back to the atmosphere. Because the air normally tends to cool in autumn, the impact of the heat released from the ocean is greatest in the September to November period. This heat release from the ocean continues even after freeze-up because the ice is thinner and less insulating than in previous decades. This ocean-to-atmosphere heat transfer affects the distribution of atmospheric pressures that, in turn, drive atmospheric circulation (Overland and Wang, 2010).

Figure 8 displays evidence that sea ice loss is already affecting the atmosphere in autumn and in winter. The figure shows the 2007–2012 warmth relative to the 1971–2000 "normal" as a function of latitude and calendar month. The pattern in Figure 8 not only highlights the polar amplification discussed earlier but also shows that the relative increase in Arctic warming is greatest in autumn and in early winter, precisely the seasonality expected from the loss of sea ice. Figure 9 shows that the warming is

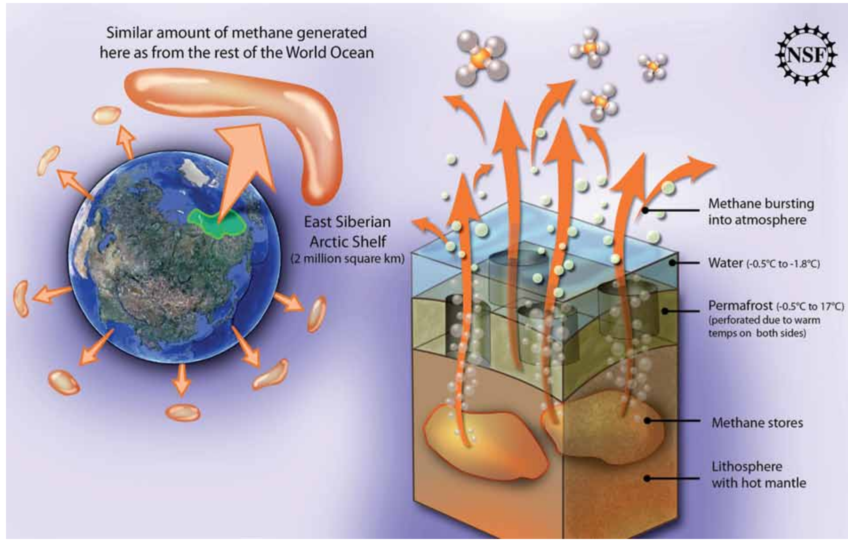



Figure 7. The subsea permafrost of the East Siberian Arctic Shelf (an area of about 2 million square kilometers) is more porous than previously thought. The ocean on top of the permafrost and the heat from the mantle below the permafrost warm it and make it permeable, allowing methane gas stored beneath it under pressure to escape into the atmosphere. The amount leaking from this locale is comparable to all the methane from the rest of the world ocean put together. Methane is a greenhouse gas more than 30 times more potent than carbon dioxide. *Courtesy of Zina Deretsky, National Science Foundation, based on Shakhova et al. (2010)*

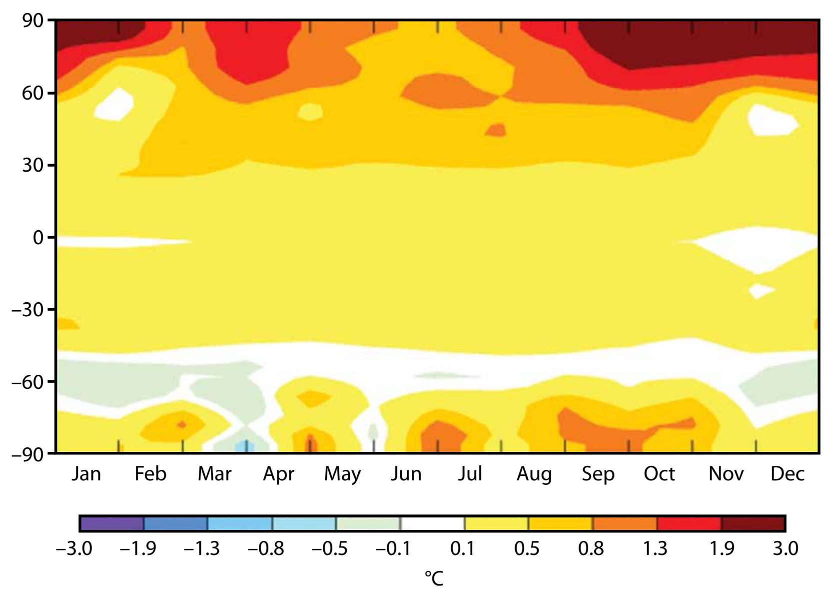



Figure 8. The warmth of 2007–2012 relative to the 1971–2000 "normal" as a function of latitude and calendar month. The data provide evidence that the loss of sea ice is already affecting the atmosphere in autumn and winter. *Courtesy of NASA GISS*

strongest near the surface, consistent with the idea that such changes are driven by changes in sea ice.

## How Are the Mid-Latitudes Impacted by Rapid Loss of Arctic Sea Ice?

The fact that the warming is strongest in autumn and at the Arctic Ocean's surface (Figures 8 and 9) is consistent with the delayed freeze-up noted above. The delayed freeze-up means that an ice-free ocean underlies the atmosphere at a time of year when reduced solar radiation favors strong atmospheric cooling. The expanded areas of open water during autumn and early winter represent not only a source of heat to the lower atmosphere but also a source of moisture. This additional moisture increases the amount of precipitation falling over the Arctic Ocean and adjacent land areas during autumn and early winter. Not surprisingly, recent decades have seen a highly significant increase in autumn (October) snow cover over Eurasia. The increase since the late 1980s has been more than 1.4 million square kilometers of snow cover per decade. The correlation between autumn ice extent in the Arctic and winter snow cover over the Northern Hemisphere is even more noteworthy. Reduced Arctic sea ice extent in autumn is associated with increased winter snow cover in large areas of eastern Asia, central Europe, and the northern half of the United States (Liu et al., 2012). But why should sea ice in autumn affect wintertime snow cover in middle latitudes? The proposed explanation for this relationship is based on reasoning about the pressure field that drives the primary feature of the Northern Hemisphere atmospheric circulation—the west-to-east flow at middle and upper levels of the mid-latitude atmosphere. This airflow includes the jet stream, with its wavelike meanders around the hemisphere.

When a column of air warms, it expands vertically. Because air pressure is the weight of the overlying air, this expansion increases the altitude at which a particular pressure will be found. Figure 9 shows that there has been an increase in elevation (the geopotential height) of the pressures in the Arctic atmosphere, as would be expected with warming. Corresponding to these increases of geopotential height are increases of pressure at all elevations, with the largest increases at the highest elevations (as in Figure 9). Higher pressures in middle and upper levels of the Arctic atmosphere favor a weakening of westerly winds (or a strengthening of easterly winds) at lower latitudes. Francis and Vavrus (2012) show that there has indeed been a weakening of the westerly winds in the middle troposphere over the past two decades. The seasonality of this weakening westerly flow shows agreement with the loss of sea ice (i.e., the westerly winds weakened primarily in autumn and winter), and the

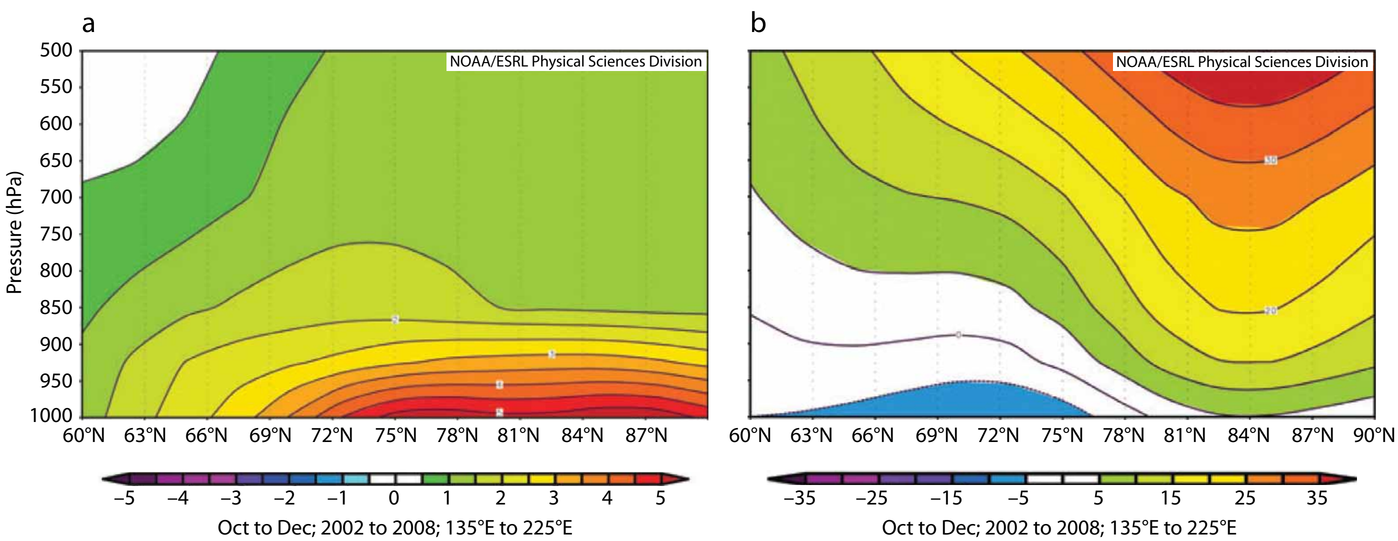



Figure 9. (a) Vertical cross-section composite plot of air temperature anomalies (°C) for the section covering the East Siberia Sea, Chukchi Sea, and Beaufort Sea from Bering Strait to the North Pole for October to December 2002–2008. (b) Vertical cross-section composite plot of geopotential height anomalies (dynamic meters) for the section from Bering Strait to the North Pole for October to December 2002–2008 over the Siberia Sea to Beaufort Sea area. The data show that Arctic warming is strongest at the ocean surface, and that there has been an increase of elevation (geopotential height) of the pressures in the Arctic atmosphere, as would be expected with warming. *From Overland and Wang (2010)*

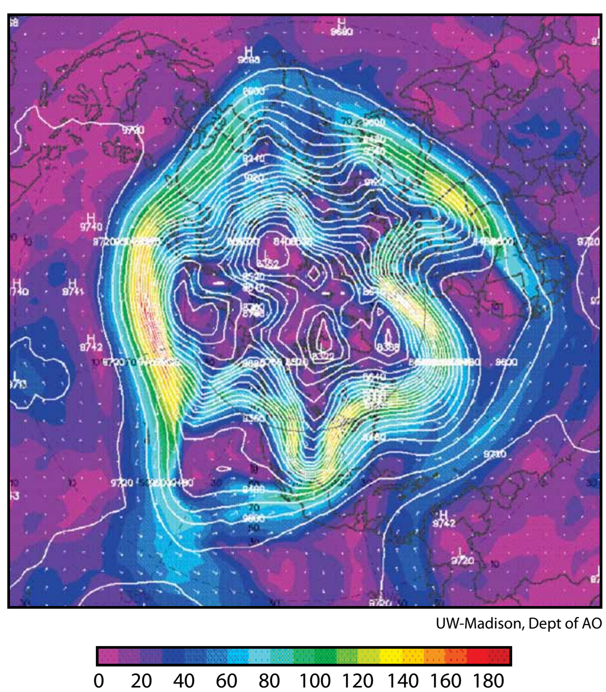
timing of the wind-pattern changes over the past few decades also agrees with the loss of sea ice (i.e., the largest decreases of westerly winds occurred after 2007).

A general weakening of the prevailing westerlies means more meandering of the airflow, including the jet stream. The jet stream typically has three to seven waves (meanders) around the hemisphere at any time (Figure 10), with northward bulges (referred to as ridges) and southward dips (referred to as troughs). As the Arctic warms relative to lower latitudes, these waves are predicted to increase in amplitude. These predictions are confirmed in an analysis of observational data by Francis and Vavrus (2012) who provide evidence that ridges have indeed strengthened more than troughs have weakened, increasing wave amplitudes in the Northern Hemisphere. However, recent work by Screen and Simmonds (2013) indicates that conclusions about recent changes in the amplitude of jet stream waves are quite sensitive to the method by which wave amplitude is evaluated.

How do these changes in wave amplitude affect weather and climate in mid-latitudes? With weaker westerlies and larger-amplitude waves, the normal west-to-east progression of waves in the atmosphere is slowed. This increases the persistence of departures from normal surface weather associated with the waves—for example, cold surface conditions beneath troughs, warm surface conditions beneath ridges. In extreme cases, features can lock into place for weeks, a situation known meteorologically as "blocking." The extended duration of anomalous weather can contribute to large departures from normal over monthly or even seasonal time scales. The study by Francis and Vavrus (2012) and other recent studies suggest that blocking is becoming more common during autumn and winter. Extreme winter anomalies, such as the extended cold periods in Europe during the 2010/11 and 2011/12 winters, and the cold, snowy winter of 2010/11 in the United States, are consistent with this notion of increased blocking. Even the extremely mild winter of 2011/12 in the United States can be viewed as an example of blocking, although the persistent characteristic in that case was the absence of deep troughs and their associated cold air masses.

Extreme winter weather, as well as other weather events, has been linked to a particular mode of variability in atmospheric pressure systems called the Arctic Oscillation. It has a positive phase, with relatively high pressure over the polar regions and low pressure at mid-latitudes, and a negative phase in which this pattern is reversed (Thompson and Wallace, 1998). The Arctic Oscillation is strongly correlated with the strength of the zonal (west-to-east) winds in middle and high latitudes. When the Arctic Oscillation enters its negative phase, the west-to-east flow weakens and north-south meanders of the airflow (including the jet stream) become more prominent, especially in the North Atlantic sector. This is an example of a blocking pattern, discussed earlier. Extensive autumn snow over Eurasia has been linked to a negative phase of the Arctic Oscillation during winter, through a complex dynamical mechanism (Cohen et al., 2012). This linkage is consistent with the previously described effects of sea ice on atmospheric wind patterns because sea ice retreat contributes to the increase of Eurasian snow cover, which in turn favors a negative (blocking) phase of the Arctic Oscillation.

A topic of recent interest is the extent to which individual storm events can be tied to the atmospheric signals




UW-Madison, Dept of AO

Figure 10. The jet stream on January 30, 2013, immediately prior to a major blizzard that affected the northeastern United States. The jet stream typically has three to seven waves (meanders) around the hemisphere at any time, with northward bulges referred to as ridges and southward dips referred to as troughs. *Courtesy of University of Wisconsin-Madison, Department of Atmospheric and Oceanic Sciences*

## Roger Revelle

For almost half a century, Roger Revelle was a leader in the field of oceanography. Revelle trained as a geologist at Pomona College and the University of California, Berkeley. In 1936, he received his PhD in oceanography from the Scripps Institution of Oceanography. As a young naval officer, he helped persuade the Navy to create the Office of Naval Research (ONR) to support basic research in oceanography and was the first head of ONR's geophysics branch. Revelle served for 12 years as the Director of Scripps (1950–1961, 1963–1964), where he built up a fleet of research ships and initiated a decade of expeditions to the deep Pacific that challenged existing geological theory.

Revelle's early work on the carbon cycle suggested that the sea could not absorb all the carbon dioxide released from burning fossil fuels. He organized the first continual measurement of atmospheric carbon dioxide, an effort led by Charles Keeling, resulting in a long-term record that has been essential to current research on global climate change. With Hans Suess, he published the seminal paper demonstrating the connection between increasing atmospheric carbon dioxide and burning of fossil fuels. Revelle kept the issue of increasing carbon-dioxide levels before the public and spearheaded efforts to investigate the mechanisms and consequences of climate change.

Revelle left Scripps for critical posts as Science Advisor to the Department of the Interior (1961–1963) and as the first Director of the Center for Population Studies at Harvard (1964–1976). Revelle applied his knowledge of geophysics, ocean resources, and population dynamics to the world's most vexing problems: poverty, malnutrition, security, and education.

In 1957, Revelle became a member of the National Academy of Sciences to which he devoted many hours of volunteer service. He served as a member of the Ocean Studies Board, the Board on Atmospheric Sciences and Climate, and many committees. He also chaired a number of influential Academy studies on subjects ranging from the environmental effects of radiation to understanding sea level change.

*Photo credit: SIO Archives, UCSD*

associated with sea ice. For example, Hurricane Sandy's highly unusual westward turn into the mid-Atlantic coast occurred when the Arctic Oscillation was in a strongly negative (blocking) phase. The absence of westerly winds indeed enabled the storm to track westward. Was this related to the unprecedented retreat of sea ice in the autumn of 2012 (Figure 4)? The connection between Arctic sea ice and Hurricane Sandy is tenuous because of uncertainties in the chain of associations linking sea ice with trajectories of individual storms. It is fair to surmise, however, that sea ice loss may have increased the odds that a late-season hurricane would take an unusual westward turn in middle latitudes. Associations between sea ice and individual events will likely be an active area of research in the coming years.

## CONCLUSION

Melting of Arctic sea ice has consequences for life both in the Arctic and in the mid-latitudes of the Northern Hemisphere. Will the rapid loss of sea ice continue into the future? Global climate models project such a continuation, especially in the warm season, through the remainder of the century. To date, the actual sea ice retreat is ahead of the pace of sea ice loss projected in nearly all climate models (Stroeve et al., 2012). Although sea ice may well increase in some years or even in multiyear periods because of natural variability in the climate system (Kay et al., 2011), current projections indicate an essentially ice-free Arctic Ocean in the summer by sometime around the middle of this century and even sooner if the actual loss continues to outpace model-projected losses. Given the accelerating sea ice loss in the past decade, the implications for middle-latitude as well as Arctic residents have grown in significance and urgency. With sea ice retreat emerging as a trigger of changes in climate throughout much of the United States, the Arctic's role as a bellwether of change is not just a concern about a remote and beautiful part of the globe. There is increasing awareness that what happens in the Arctic does not stay in the Arctic.

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