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THE CHANGING ARCTIC SEA ICE COVER

Background NASA image courtesy of the Digital Mapping System team, and Operation IceBridge Arctic 2011

ABSTRACT. Arctic sea ice cover has declined over the past few decades. The end of summer September ice extent reached a record minimum in 2007. While there has been a modest recovery since then, the past four years (2007–2010) show the lowest sea ice extent in the 30-year satellite record. Submarine and satellite ice thickness measurements show a factor of two decrease (3 m to 1. 4 m) from 1957–1976 to 2003–2007. There has been a shift from sea ice cover consisting mainly of ice more than a year old to ice less than a year old. These changes have resulted in a less robust ice cover that is more sensitive to dynamic and thermodynamic forcing. Changes in atmospheric pressure fields in recent years have affected the distribution of ice in the Arctic Basin. Increases in advected ocean heat through Bering Strait may serve as a trigger for ice retreat in the Chukchi and Beaufort Seas. More open water has led to enhanced solar heat input and warming of the upper ocean and greater ice melt. While there may not be a tipping point for Arctic sea ice cover, positive feedbacks do contribute to rapid changes. The declining Arctic sea ice cover is affecting human activities.

INTRODUCTION

Arctic sea ice cover is in decline. Observations show a reduction in summer ice extent (Serreze et al., 2007; Stroeve et al., 2007; Comiso et al., 2008), a decrease in ice thickness (Rothrock et al., 2008; Giles et al., 2008; Haas et al., 2008; Kwok and Rothrock, 2009), and a shift from primarily perennial ice pack to seasonal ice (Rigor and Wallace, 2004; Maslanik et al., 2007; Nghiem et al., 2007). Many factors have been identified as contributing to this decline (Serreze et al., 2007), including warming trends (Johannessen et al., 2004; Rothrock and Zhang, 2005; Overland et al., 2008), preconditioning of the ice (Rigor et al., 2002; Drobot and Maslanik, 2003; Nghiem et al., 2006; Lindsay et al., 2009), changes in atmospheric circulation and ice motion (Makshtas et al., 2003; Nghiem et al., 2007; Rampal et al., 2009), shifts in cloud cover (Francis et al., 2005; Kay et al., 2008; Schweiger et al., 2008), advected ocean heat (Polyakov et al., 2003, 2010; Woodgate et al., 2006, 2010), and ice albedo feedback (Perovich et al., 2007, 2008). These changes in the physical state of the ice cover are affecting the Arctic Ocean ecosystem and also human activities.

Ice albedo is a prominent sea ice feedback. Albedo is the fraction of incident light that is reflected. Snow-covered ice has a large albedo, reflecting 85% of the incident solar energy (Perovich et al., 2002), while bare, melting ice has an albedo of approximately 0.65. In contrast, open water has an albedo of only 0.07 (Pegau and Paulson, 2001). As the ice cover declines and the sea ice area decreases, there is more open water. More open water means more absorbed solar radiation. This absorbed solar radiation contributes to additional melting and more open water and more absorbed solar heat. And so the feedback continues, building upon itself.

Arctic sea ice cover acts both as a climate change indicator and as an amplifier. It is vast in areal extent, covering millions of square kilometers, but it is just a thin ice veneer, only a few meters thick. Thus, the ice cover is a sensitive indicator of warming or cooling trends. Through feedback mechanisms, like ice albedo, it can also amplify changes.

This paper reviews recent observations of the changes in sea ice extent, age, and thickness. It explores our understanding of observed changes by examining the causes of the large decrease in ice extent in the summer of 2007. The paper also discusses the role of feedback processes and tipping points in future trajectories of the ice cover, and examines the impacts of declining Arctic sea ice cover.

OBSERVING

Ice Extent

Ice extent has become the prime indicator of the health of sea ice cover. There is a 30-year continuous record of ice extent in passive microwave satellite observations. Figure 1a plots the time series of monthly ice extents from November 1978 to December 2010 (Fetterer et al., 2010). Large oscillations are evident, with extreme ice extents ranging from 16 million km^2 to just over 4 million km^2. These oscillations are simply the seasonal cycle. Ice grows from fall through winter, reaching a peak in March, and then declines through

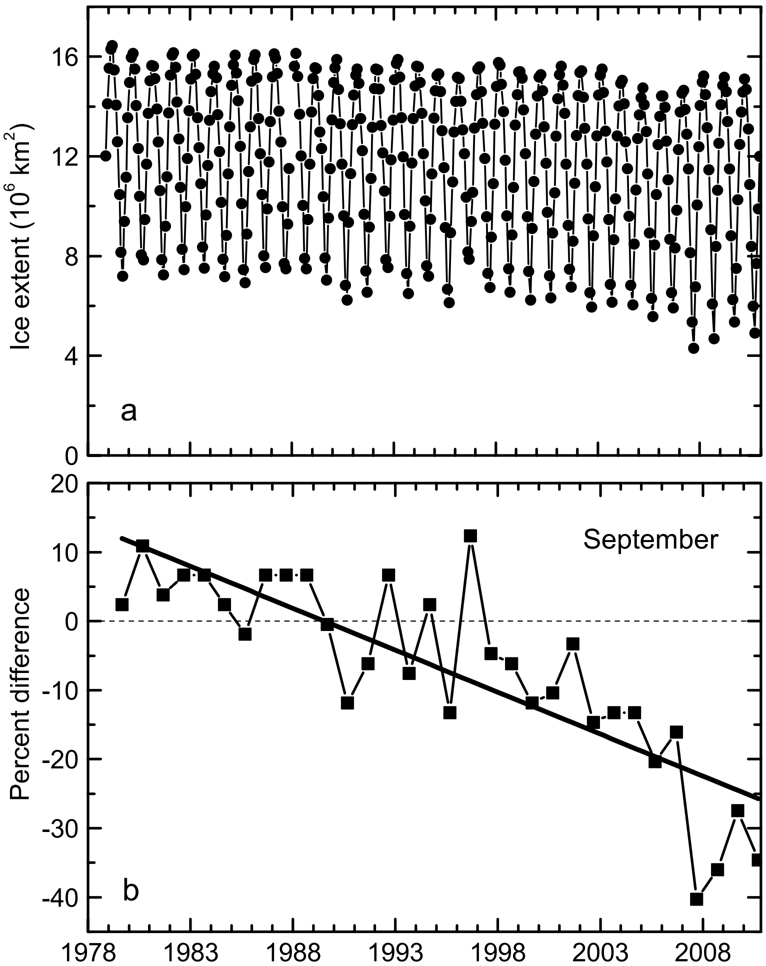

Figure 1. (a) Monthly values of Arctic sea ice extent determined from passive microwave satellite data. The data set is from November 1978 to December 2010. (b) The percent difference in September ice extent (the month of ice extent minimum) relative to the mean value for the period 1979–2000. Based on a least squares linear regression for the period 1979–2010, the rate of decrease for September ice extent is –12.8% per decade.

spring and summer as the melt season progresses. This observation confirms that ice extent is sensitive to changes in temperature. However, changes in ice extent due to the seasonal cycle are so large that they tend to obscure any signal due to interannual variability or climate change.

The strong seasonal cycle can be eliminated by focusing on a single month. September is typically selected because it is at the end of summer melt and shows the minimum annual ice extent. Figure 1b plots the percent differences in September ice extent, comparing September averages from 1979 to 2000 (Fetterer et al., 2010). The September values show significant interannual variability. For example, there was a record minimum in September 1995 followed by a record maximum in 1996. However, a downward trend is evident. A linear least squares fit to the data gives a decrease in September ice extent of –12.8% per decade over the period 1979–2010, with a standard error of 1.6% per decade. The decrease appears to have accelerated, with September 2007 being the record minimum ice extent and the past four Septembers having the four smallest ice extents. There is considerable discussion as to whether the last four years represent an acceleration in ice loss or a new quasi-equilibrium state. The satellite observational record is unequivocal: Arctic sea ice extent has declined in the past few decades.

Ice Age

The age of the ice is another important parameter that describes the state of the ice cover. There are two basic types of sea ice: first-year ice and multiyear ice. Multiyear ice is defined as ice that has survived a summer melt season. First-year ice that survives through September "graduates" into multiyear ice. Multiyear ice is primarily confined to the Central Arctic, the Canadian Archipelago, and a tongue of ice moving down Fram Strait on the east side of Greenland. First-year ice can be found anywhere, but virtually all of the ice in the Bering Sea, the Sea of Ohkotsh, Hudson Bay, and the Gulf of Bothnia is first-year ice that forms in winter and completely melts in spring and summer. Multiyear ice tends to be thicker and thus more robust than first-year ice to the environmental forcing of extreme melt years. Thus, the fraction of multiyear ice is a simple measure of the

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health of the ice cover.

The age of sea ice can be estimated from satellite observations of its radar backscatter signature (Nghiem et al., 2006, 2007) and by tracking ice parcels over several years (Rigor and Wallace, 2004; Maslanik et al., 2007). Maslanik et al. (2007) assembled a record of ice age since the early 1980s using the ice parcel tracking method. Figure 2 shows sea ice age results for the first week of March in (a) 1988, (b) 2008, (c) 2009, and (d) 2010 (Maslanik et al., 2007). There has been substantial loss in the oldest ice types within the Arctic Basin in recent years compared to the late 1980s. The loss is acute for ice five years and older, which comprised most of the multiyear pack in 1988 and was just a small fraction in 2010. Radar backscatter results from Nghiem et al. (2007) demonstrate that in the past decade, multiyear sea ice area decreased at a rate of 1.5 x 10^6 km^2 per decade. This rate is three times the loss rate for the period 1970–2000.

The record summer ice extent minimum of 2007 was, in turn, followed by a record multiyear ice minimum in March 2008. Since 2008, there has been a modest increase in multiyear ice in 2009 and again in 2010, due mainly to an increase in two- and three-year-old ice. This increase was supported by a strong atmospheric circulation pattern during winter 2010 that kept most of the two- to three-year-old ice in the central Arctic. Even with this increase, 2010 had the third lowest March multiyear ice extent since 1980. The decreases in multiyear ice are due to a combination of enhanced advection out of Fram Strait (Nghiem et al., 2007) and ice melting in the Arctic. For example, in 2008, a lobe of very old, thick ice from north of the Canadian Archipelago drifted down into the Beaufort and Chukchi Seas. Despite being old and presumably relatively thick, this area of ice did not survive the 2009 summer melt period (Figure 2c). Similarly, in March 2010, there was another narrow band of old ice north of Alaska in the Chukchi and Beaufort Seas that melted during the summer of 2010. The greatest change between 1988 and 2010 has been the massive decrease of very old (five years and older) ice, making the ice cover more susceptible to warming trends and interannual fluctuations.

Ice Thickness

Ice age may be related to ice thickness, but it is only a proxy. Ice thickness, as well as ice extent, is needed to determine the volume of sea ice present. Unfortunately, ice thickness is difficult to obtain. There is no Arctic-wide, 30-year time series of ice thickness as there is for ice extent. The best source of early ice thickness observations is surveys conducted by nuclear submarines dating back to the 1950s. Ice thickness profiles were calculated from upward-looking sonar measurements. The submarine data sets were limited to snapshots in

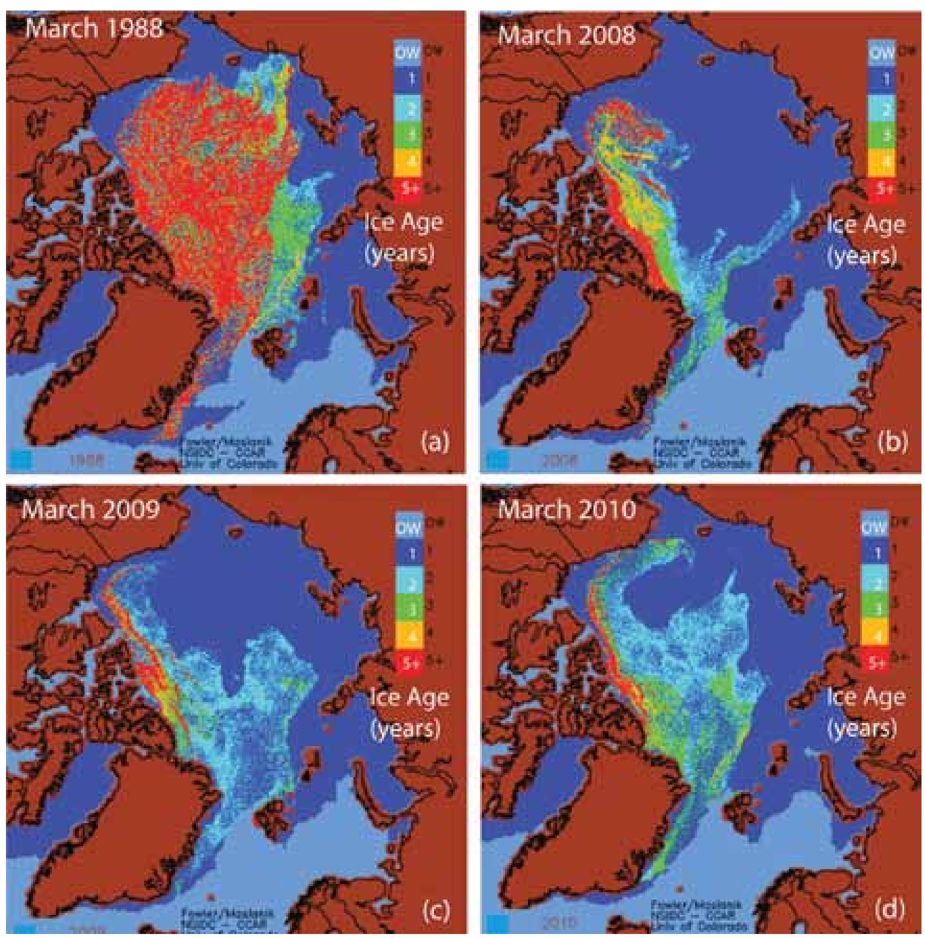

Figure 2. Sea ice age derived from drift tracking of ice floes for the first week of March in (a) 1988, (b) 2008, (c), 2009, and (d) 2010. The panels illustrate the substantial loss in the oldest ice types within the Arctic Basin in recent years compared to the late 1980s. *Figure courtesy of National Snow and Ice Data Center, J. Maslanik and C. Fowler*

space and time—infrequent cruises conducted at various locations at different times of year. It has only been in recent years that satellite-based altimetry using light detection and ranging (Kwok et al., 2004) and radars (Laxon et al., 2003) has been applied to estimate ice thickness, providing broader and more frequent coverage.

Rothrock et al. (1999) analyzed the submarine data by dividing the submarine-gathered snapshots of ice thickness into seven separate regions in the Central Arctic (Figure 3a) and two separate time periods. Ice thicknesses were adjusted to mid-September values. The two periods are the early years (1958 through 1976) and the 1990s (1993 through 1997). All regions showed a substantial decrease in ice thickness from the early years to the 1990s (Figure 3b). The average decrease was 40%, from an ice thickness of 3 m to less than 2 m.

Kwok and Rothrock (2009) used satellite lidar altimetry observations to temporally extend the submarine observations to include the years 2003–2008. The combined submarine and satellite record shows a long-term trend of sea ice thinning over the three decades of the joint record. Though the decrease was smaller for 2003–2008, the downward trend in thickness continued (Figure 3b). The average September ice thickness decreased from 3.0 m (1958–1976) to 1.6 m (1993–1997) and then to 1.4 m (2003–2007), so that the 2003–2007 ice cover was only half as thick as that for 1958–1976.

Examining the satellite observations in more detail shows no downward trend in the average mid-winter thickness of first-year ice of about 2 m. This observation means that the winter growth of first-year ice has not changed appreciably from 2004–2008. However, when including multiyear ice, there was a remarkable overall thinning of ~ 0.6 m in thickness between 2004 and 2008. First-year ice covered more than two-thirds of the Arctic Ocean in 2008. Combining the decreases in multiyear ice area and multiyear ice thickness shows a net loss of multiyear ice volume of more than 40% in the four years since 2005. There was an increase in first-year ice cover volume due to increased overall areal coverage (Figure 2). The total sea ice volume and average thickness declines are explained almost entirely by loss of multiyear sea ice due to melting and ice export. These changes in ice thickness and ice age have resulted in seasonal ice becoming the dominant Arctic sea ice type, both in terms of area coverage and of volume.

a

b

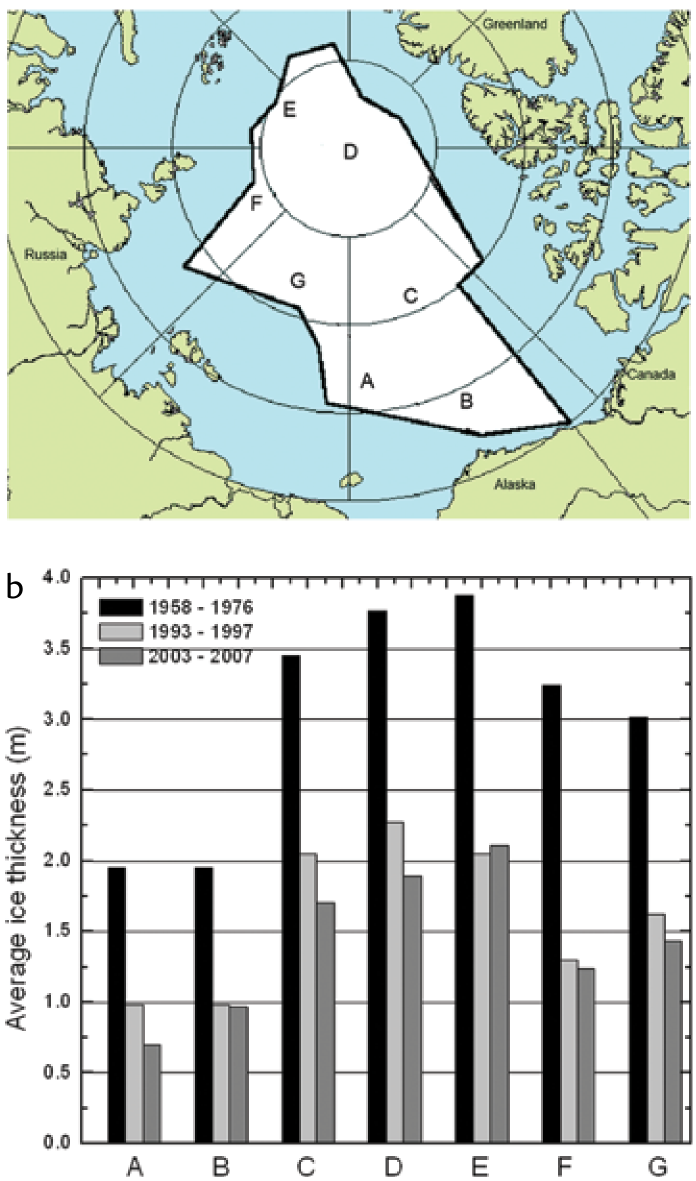

Figure 3. (a) Seven regions where submarine records were analyzed by Rothrock et al. (1999). The black line and white area denote the region where submarine thickness records were released. (b) Average ice thickness in the seven regions for the time intervals 1957–1976, 1993–1997, and 2003–2007. Data in (b) are from Kwok and Rothrock (2009).

UNDERSTANDING

The observational record is clear. Arctic sea ice cover is in decline. During the past three decades there has been a reduction in ice extent, a decrease in ice thickness, and a shift from multiyear ice to first-year ice. To determine future ice cover trajectories, the causes of this decline must be understood. Ultimately, sea ice cover is governed by dynamics, resulting in ice motion, and thermodynamics, causing ice growth and melt. To understand the observed changes, we must assess the impacts of changing dynamics and thermodynamics on the ice cover. As a first step toward understanding, we examine the specific case of the summer of 2007 when the ice cover had a record annual decrease to reach a record minimum ice extent.

The Summer of 2007

The record minimum September 2007 ice extent of only 4.2 million km^2 was shocking. It was a decrease of 1.7 million km^2 from the previous September. Stroeve et al. (2007) compared the observed September 2007 ice extent to general circulation model runs and found it to be significantly below all model runs and millions of square kilometers less than the ensemble mean.

Figure 4 puts the 2007 loss in a geographic context by showing the ice loss between 1980 and 2007 (red shaded area of map). There have been major ice retreats off the coasts of Siberia and Alaska. In 2007, the Northwest Passage through the Canadian Archipelago was ice-free and the Northern Sea Route was almost completely open.

The massive melt of 2007 garnered considerable attention, and many factors were offered to explain the ice loss. These factors included warmer temperatures, preconditioning of the ice (a term used to describe general thinning of the ice over several years), changes in atmospheric circulation, ice motion, ocean heat advection, clouds, and solar heating of leads.

In a sense, the summer of 2007 began years earlier, with a preconditioning of the ice (Stroeve et al., 2008). There had been a significant decline in the amount of older multiyear ice in the Arctic prior to 2007 (Rigor and Wallace, 2004; Nghiem et al., 2007; Maslanik et al., 2007) due to melting and export of multiyear ice from the Arctic Basin. A decrease in multiyear ice implies a decrease in ice thickness. Using an ice-tracking algorithm and satellite ice thickness observations, Maslanik et al.

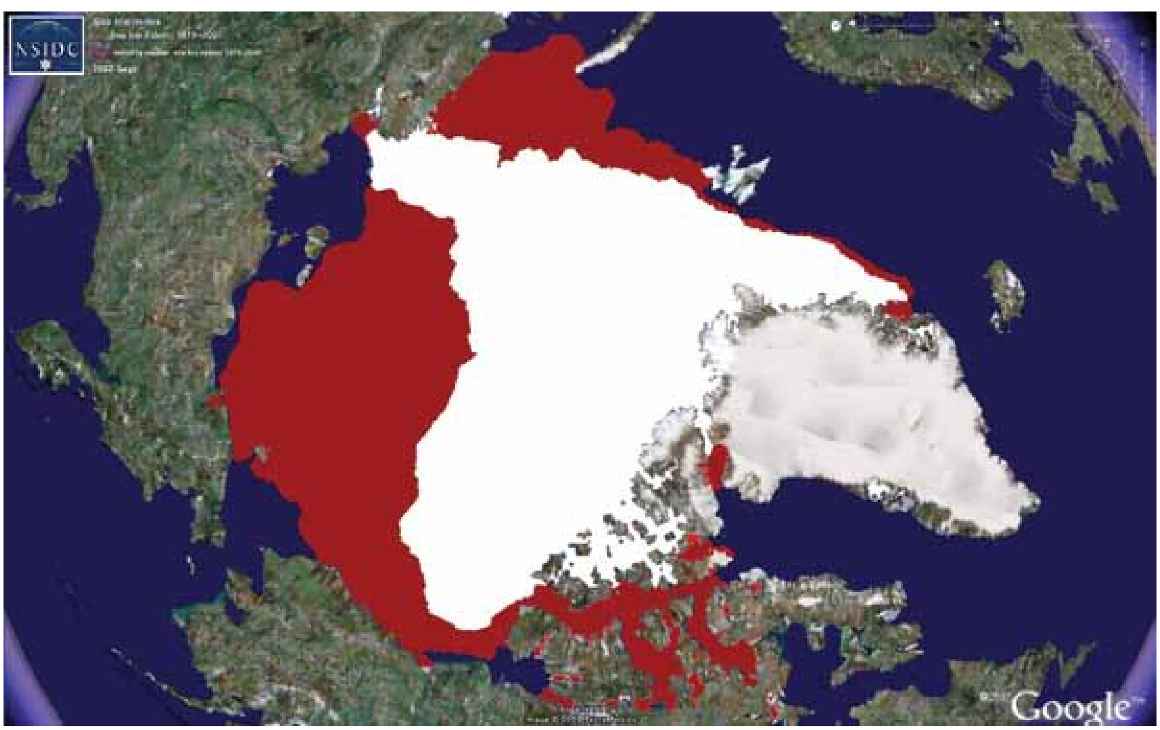

Figure 4. Sea ice extent in September 1980 (red and white) and September 2007 (just white). Red area denotes change between 1980 and 2007.

(2007) found a decrease in average Arctic Ocean ice thickness from 2.6 m in 1987 to 2.0 m in 2007. Most notable was the large loss of ice thicker than 3 m. A younger, thinner ice cover is less robust, mechanically weaker, and more vulnerable to changes in atmospheric and oceanic forcing (Shimada et al., 2006; Kwok, 2007; Maslanik et al., 2007; Ogi and Wallace, 2007; Serreze et al., 2007; Gascard et al., 2008; Stroeve et al., 2008).

The advection of ocean heat from lower latitudes contributed to the enhanced ice melt in 2007. Woodgate et al. (2010) showed substantial ocean heat flux through Bering Strait to the Chukchi Sea due to warm water temperatures and increased flow. The sea ice melt due to this advected heat could provide a trigger for the ice albedo feedback and thus further losses. Heat stored in the water column would retard freezing in the fall, leading to a thinner ice cover. Polyakov et al. (2010) found warming of intermediate-depth (150–900 m) Atlantic water in the Arctic Ocean. Even though this water is well below the bottom of the ice, it may result in an increase of 0.5 W m^{-2} in the ocean heat flux to the ice.

Wind forcing played a role in the 2007 decline (Nghiem et al., 2007). During the summer of 2007, there was a pronounced atmospheric low-pressure zone over the Barents Sea and a strong high-pressure zone over the Canadian Basin. This condition resulted in geostrophic flow across the Arctic with persistent winds along the Transpolar Drift Stream. The combination of these winds and the thinner, weaker ice resulted in enhanced ice motion, which contributed to export out Fram Strait (Nghiem et al., 2006, 2007) and added deformation of ice north of Greenland. One example of this enhanced motion was the drift of the vessel *Tara* (Gascard et al., 2008). *Tara* was frozen into the ice in the Laptev Sea in September 2006, with the intent of following the drift of Nansen's *Fram*. While the *Tara* drift track was similar to that of *Fram*, it completed its trans-Arctic drift in only 15 months, three times faster than expected. The combination of thin ice and strong winds along the Transpolar Drift Stream resulted in greater ice velocities and more ice motion in 2007. However, it is difficult to determine the precise volume of ice exported out Fram Strait, as the volume also depends on ice thickness, ice concentration, and the width of the ice stream. Estimates of ice export calculated by Spreen et al. (2009) showed no significant change in Fram Strait ice export in recent years.

"THESE CHANGES IN THE PHYSICAL STATE OF THE ICE COVER ARE AFFECTING THE ARCTIC OCEAN ECOSYSTEM AND ALSO HUMAN ACTIVITIES."

The same atmospheric pressure pattern resulted in a flow of warm air into the central Arctic, with winds from the North Pacific flowing across the North Pole. This warm air resulted in positive temperature anomalies over most of the Arctic Ocean in 2007. These warm temperatures in spring and summer caused additional melting and a reduction in ice extent, which in turn contributed to atmospheric warming. A reduction in ice extent means an increase in open water as well as an increase in solar heat absorbed into the ocean. The largest atmospheric warming was in the fall with anomalies of +6°C over much of the Arctic (Richter-Menge et al., 2009). The same summer southerly wind anomaly moved ice out of the Pacific sector of the Arctic Ocean, also increasing the area of open water. Replacing ice with open water reduces albedo and leads to an increase in solar heat input to the upper ocean.

A decrease in cloudiness over the western Arctic Ocean in 2007 compounded the increase in solar heat input due to changes in albedo. Kay et al. (2008) found a decrease in summertime ice cover of 16% between 2006 and 2007, resulting from an increase in downwelling solar radiation of 32 W m^{-2}. However, model simulations by Schweiger et al. (2008) indicated that the enhanced solar heating resulted in only a modest increase in ice surface melt in 2007. The impact of the added downwelling solar radiation is greatest for open water with its small albedo. More open water and more downwelling sunlight results in more heat deposited in the upper ocean, which can cause warming of the upper ocean. Steele et al. (2008) reported upper ocean summer warming anomalies of up to 5°C in the Chukchi and Beaufort Seas.

A warmer upper ocean can result in enhanced melting on the bottom and the lateral edges of ice floes. Examining the annual cycle of mass balance in the Beaufort Sea provides insight into the nature of the ice loss in this region. Figure 5 presents a year-long time series of air, ice, and ocean temperatures as well as ice growth and melt from September 2006 to November 2007. The ice examined was a substantial multiyear floe with a thickness of 2.8 m at the end of summer 2006. Winter conditions were fairly usual for the Beaufort Sea with temperatures as cold as –45°C, a maximum snow depth of 0.4 m, and ice growth of 0.33 m. Surface melt in 2007 was typical for the Beaufort Sea, with melt starting in early June and a total of 0.7 m of surface melt. The difference in 2007 was the extremely large 2.1 m of bottom melting. There was a gradual buildup of heat in the upper ocean in July and August. Bottom melt rates increased throughout the summer, reaching peak values of 0.1 m d^{-1} in late August. Perovich et al. (2008) demonstrated that solar radiation was the source of heat needed for the large amount of bottom melting. In the summer of 2007, there was an increase of the area of open water near the study site. This situation resulted in a factor of five positive anomaly in solar heat input to the upper ocean and provided ample heat for the observed bottom melting. This solar heat anomaly is evidence of a contribution from the ice albedo feedback.

The Arctic summer of 2007 has been called a perfect storm of sea ice loss. Many factors combined to cause the loss. In a modeling study, Zhang et al. (2008) suggest that about 70% of the 2007 summer ice loss was due to thermodynamics (surface, bottom, and lateral melt) and 30% was due to ice dynamics (increased wind-driven advection). Kwok and Cunningham (2010) confirmed the thermodynamic losses by finding increasing melting of multiyear ice in the Beaufort Sea from 1993 through 2009. The atmospheric pressure pattern resulted in winds that increased ice export from the Transpolar Drift Stream and increased atmospheric heat advection from the western Pacific to the Arctic. Advected ocean heat from lower latitudes triggered ice melt. High pressure in the Beaufort Sea decreased

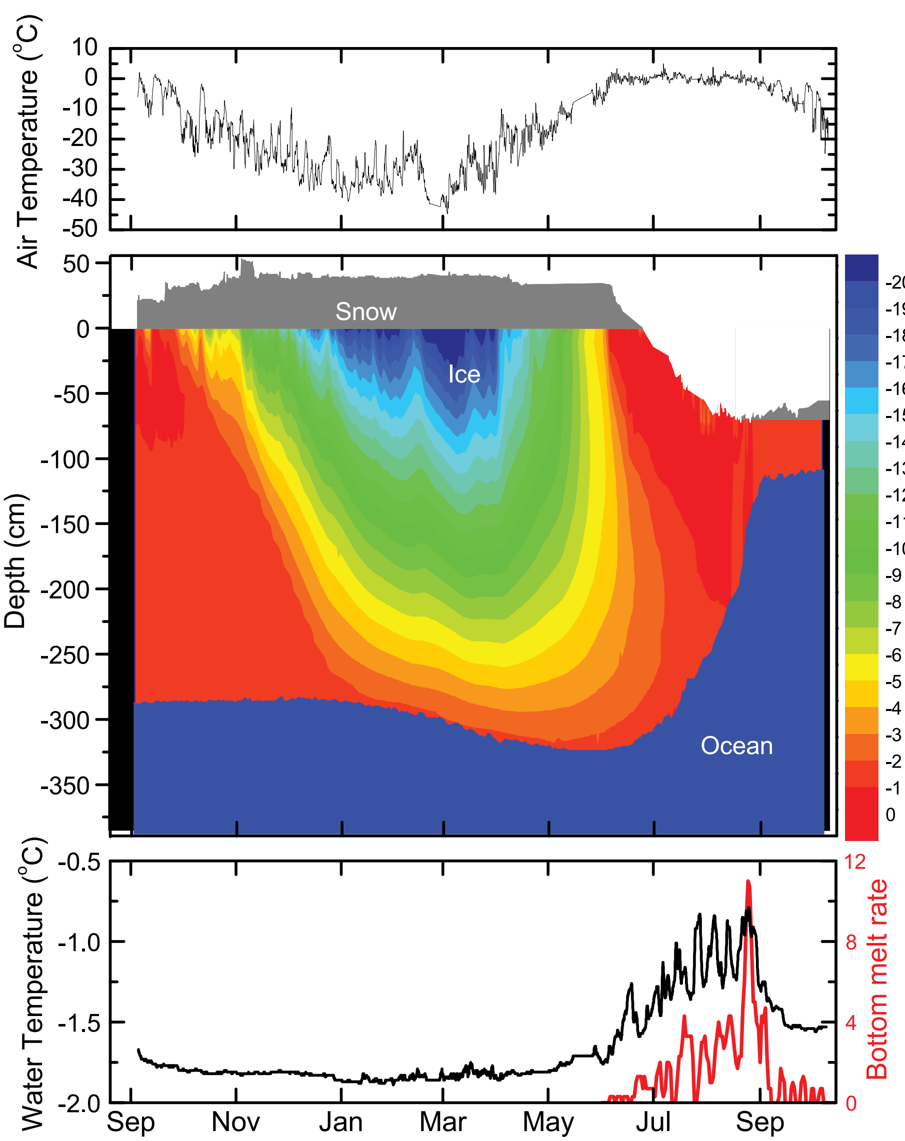

Figure 5. Time-series results for an ice mass balance buoy deployed in the Beaufort Sea from August 2006 to November 2007. Plot includes air temperature (top panel); internal ice temperature, snow depth, and ice thickness (middle panel); and ocean temperature beneath the ice (black) and bottom melt rate (red) (bottom panel). In the middle panel, the gray shaded area represents snow, the black areas are missing data, and the dark blue represents the ocean. *From Perovich et al. (2008)*

cloudiness and increased solar heat input. More open water and more incident solar radiation warmed the upper ocean, enhancing ice melt and initiating ice albedo feedback that further enhanced ice melt. If indeed the summer of 2007 was a perfect storm, it was a storm that befell an increasingly fragile ice cover. Years of gradually warming air temperatures had left an ice cover that was susceptible to the extreme atmospheric and oceanic forcing of 2007.

Feedbacks and Tipping Points

When projecting future trajectories of sea ice cover, the role of feedbacks, such as that of ice albedo, is of particular interest because of their ability to either amplify or dampen changes. Perovich et al. (2007) investigated the effect on solar heat input to the ocean of changes in the area of open water in the Arctic sea ice cover. A synthetic approach was taken using incident irradiances from reanalysis products, field observations of ocean albedo, and satellite-derived ice concentrations to calculate the amount of solar heat input directly to the upper ocean for every day from 1979 through 2005 for all areas in the Arctic where sea ice was present.

Figure 6 maps the trends in annual solar heat input directly to the ocean from 1979 to 2005. Positive trends are pervasive, covering 90% of the area. The mean trend is a modest 0.8% yr^{-1}. However, peak trends are 4% per year, resulting in a more than doubling of the solar heat input from 1979 to 2005. This increased solar heat input to the ocean contributed to warming of the upper ocean (Steele et al., 2008) and to enhanced melting on the bottom of the ice (Perovich et al., 2008).

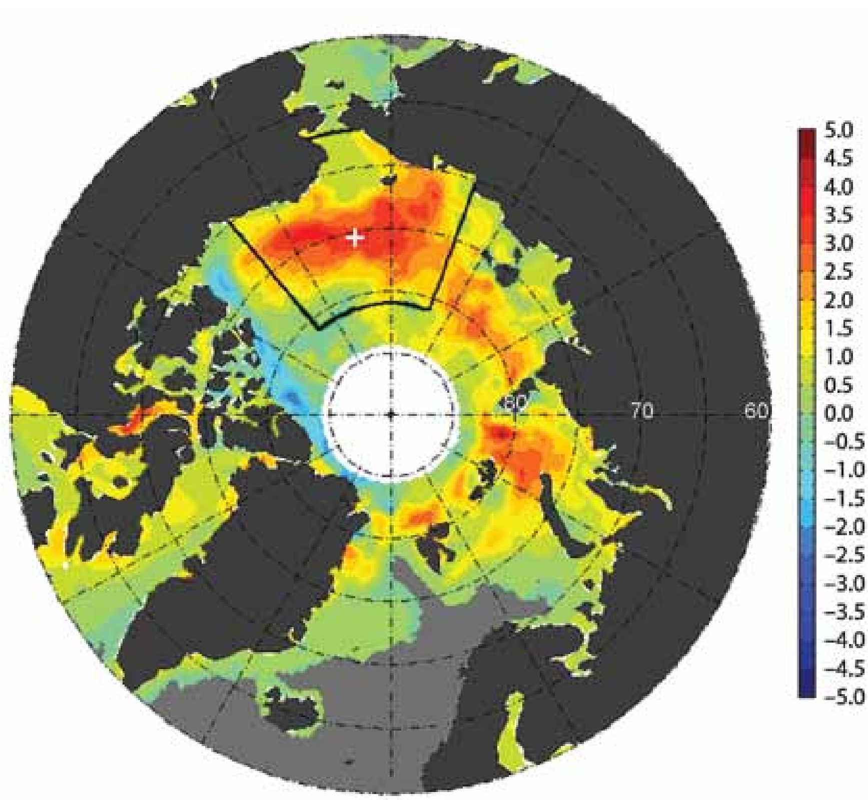

Figure 6. Map of the linear trend of annual total solar heat input directly to the ocean, with units of percent per year from Perovich et al. (2007).

The presence of positive ice albedo feedback raises concerns regarding sea ice tipping points (Lindsay and Zhang, 2005). Using the standard tipping point metaphor, consider the Arctic sea ice cover to be a rowboat. Interannual variability in ice extent rocks the boat back and forth, but with no change to the stable state of the boat/ice cover. However, add a general warming trend, and there is a general decline of ice cover plus the natural variability. The rowboat is leaning to one side as it is being rocked. For the rowboat, there is a tipping point where a new equilibrium is reached, upside down and full of water. From this new equilibrium, it is difficult to return to the old state. For sea ice, this tipping point is a reduction in ice area, amplified by ice albedo feedback, resulting in a precipitous decline to an ice-free Arctic Ocean in summer. The ice-free state absorbs more solar heat in the summer, retarding freezing in the fall and winter, leading to a thinner winter ice cover that completely melts in summer. In this fashion, the ice-free state continues even if there is a return to cooler temperatures.

The strengths of the feedback processes determine whether sea ice has a tipping point (Curry et al., 1995). Model studies by Flato and Brown (1996) and Stern et al. (2008) show bifurcating scenarios with two stable states, indicative of a tipping point. Eisenmann and Wettlaufer (2009), using a simple sea ice model, determined a trajectory with a tipping point under extreme warming where there is no ice in summer or winter. Other studies, using both simple models (Winton, 2006a; Eisenman and Wettlaufer, 2009) and general circulation models (Holland et al., 2006), show rapid changes in sea ice, but without tipping points. Tietsche et al. (2011), using a general circulation model, show that an ice-free summer was not a tipping point. Their calculations show that a sea ice-free summer Arctic did result in more solar heat input to the ocean, but this heat input was compensated by enhanced heat loss to the atmosphere and rapid growth of winter ice. The end result is a rapid return of summer ice from an ice-free state. The lack of a tipping point is due in part to modeled ice albedo feedback that is weaker than in previous studies (Winton, 2006b, 2008; Bitz, 2008). The feedback may be weaker because the largest decrease in ice area occurs in September, when the solar incident irradiance is decreasing rapidly. Another brake on the sea ice decline is the rapid growth of thin ice. This rapid growth makes the ice less sensitive to the length of the growth season and allows the ice to recover quickly if there is atmospheric cooling. While there may not be a tipping point for the Arctic sea ice cover, rapid changes amplified by feedbacks do occur.

IMPACTS OF CHANGE

An oft-asked question is: "When will the Arctic Ocean be ice-free in summer?" It is a difficult, somewhat speculative question to answer. Current conventional wisdom calls for a summer sea ice-free Arctic Ocean in a few decades, but projections range from a few years to centuries. A simpler question is: "When will the decline in the Arctic sea ice cover impact human activities?" The answer is that it already has. The decline of the summer sea ice cover has already affected Arctic coastal communities, shipping, and resource exploration.

The reduction in sea ice extent has impacted coastal communities in several ways. With sea ice forming later in the fall, there is no protection from wave action induced by autumn storms, resulting in increased coastal erosion. Shorefast sea ice serves as a highway for travel and for subsistence hunting of marine mammals. However, the usability of the ice highway is being limited by later ice formation and earlier ice melt.

The confluence of higher energy prices and a reduced Arctic sea ice cover have led to increased natural resource exploration in the Arctic continental shelf. This region is believed to contain one-eighth of the world's undiscovered and recoverable oil and one-third of the natural gas (Grom, 2009). Extracting this oil and gas is complicated by a lack of infrastructure, the presence of sea ice, and extreme winter conditions with severe cold and months of darkness. A major concern is the inability at present to respond to an under-ice oil spill.

The decreases in summer sea ice extent and ice thickness have increased Arctic marine shipping and tourism. In the past decade, there has been an increase in cruise ships in the Arctic around Greenland and even north of Alaska (AMSA, 2009). At present, most of the shipping in the Arctic is directed at resupplying Arctic communities, or shipping within the Arctic. However, as ice cover declines, there is growing interest in using the Northern Sea Route (north of Russia) and Northwest Passage (via the Canadian Archipelago) as trans-Arctic shipping routes, routes that can be significantly shorter than lower-latitude alternatives. For example, London to Tokyo is 24,100 km via the Panama Canal and 20,900 km via the Suez Canal. In contrast, the distance is 13,700 km across the Northwest Passage and 12,900 km by the Northern Sea Route (AMSA, 2009). There are several limitations to Arctic shipping: lack of infrastructure, including deepwater ports; areas with inadequate navigation charts; sparse meteorological data; and limited emergency response capabilities.

Finally, there is the question: Who owns the Arctic Ocean? This question is not new, but it has greater urgency now because of increased possibilities for shipping and easier accessibility of Arctic marine resources. The issue is compounded by United Nations Convention on the Law of the Sea (UNCLOS) considerations in defining territorial boundaries. In recent years, there has been extensive seafloor mapping for UNCLOS claims. The area that can be claimed by each of the five Arctic Ocean nations (Canada, Denmark, Norway, Russia, and the United States) is still being determined, but it is likely that most of the Arctic Ocean will be claimed. While who owns the Arctic may still be unclear, it is certain that the challenges facing the Arctic Ocean know no boundaries. International cooperation is needed to meet these challenges.

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