Arctic Sea Ice and a Changing Climate

Daniel Swain

Writer's Comment: These pieces were written in response to two separate assignments in Victor Squitieri's UWP 104E Scientific Writing class—to write a "popular" science article targeted towards a lay audience, and later to assemble a formal scientific literature review. I chose to write about Arctic sea ice in the context of climate change for both pieces because of the widespread interest, intensive and ongoing scientific research, and (most importantly) the fundamental misunderstandings surrounding the subject today. In the lay article, I attempt to provide an engaging narrative that is both understandable to a broad audience and true to the established science that underlies the topic. The literature review, intended for a narrower and more specialized audience, focuses with greater depth on several recent studies and publications. Many thanks are due to Professor Squitieri, who provided not only the impetus for both these pieces but also immensely helpful and expert stylistic guidance through the writing process.

—Daniel Swain

Instructor's Comment: Contemporary scientists need to communicate effectively not only with their professional colleagues but also with a wide gamut of readers, often including scientifically unsophisticated decision-makers and lay audiences from disparate backgrounds. In the two papers that follow, Daniel Swain demonstrates a genuinely impressive ability to target both such audiences with poise and precision. In his literature review, Swain addresses with assurance an audience of atmospheric scientists, updating his wider research community on recent experimental findings and assessing the extent to which measurements of current Arctic sea ice phenomena may permit intra-annual climate forecasting. In his pendant lay article, Swain engagingly invokes his firsthand experience in the crepuscular frontier community of Barrow, Alaska; deftly interweaving basic elements of atmospheric science with a compelling personal narrative, he helps a general audience grasp some of the ways in which dramatic changes in Arctic sea ice are affecting not only the community of Barrow but also the larger ecosystem. To target either a scientific or a lay audience successfully requires significant effort, grace and skill; the even rarer ability to target both such audiences with equal success renders Daniel Swain a very special writer.

—Victor Squitieri, University Writing Program

Review Article

Ongoing Changes in Arctic Sea Ice and Impacts on Northern Hemisphere Atmospheric Circulation

Abstract

Sea ice in the Arctic Ocean has been decreasing since at least the late 1970s. The atmospheric circulation of the Northern Hemisphere can respond strongly to reductions in sea ice, leading to changes in hemispheric wind patterns and the distribution of tropospheric temperatures and sea level pressures. This review analyzes several recent publications in order to summarize (i) the known physical processes that contribute to sea ice–atmosphere linkage, (ii) observational evidence that such linkage has led to ongoing climate change, and (iii) projections for future ice-forced changes in climate. On the basis of these studies, this paper also demonstrates the preliminary feasibility of using sea ice conditions as a climate prediction tool.

1. Introduction

The Arctic is presently in a state of great flux. Since reliable satellite estimates first became available in the late 1970s, measured aerial sea ice extent has declined by about 10% each decade, and an acceleration of this trend has become evident in the past five to ten years (Budikova 2009; Deser et al. 2010). Roughly half of the decline to date has been linked to anthropogenic forcing (namely greenhouse gas emissions), whereas the rest has been attributed to the internal variability of the ice–atmosphere system (Budikova 2009). These large reductions in Arctic sea ice extent have been linked to changes in both small and large-scale atmospheric circulations (Overland and Wang 2010), some of which have become especially pronounced following recent extreme sea ice minima (Budikova 2009). As greenhouse gas emissions continue to increase, anthropogenic forcing is expected to dominate the ice–atmosphere system and lead to the development of a seasonally ice-free Arctic Ocean within 15–50 years (Deser et al. 2010). The presence of widespread open water in the Arctic Ocean during summer is already driving major changes in the general atmospheric circulation and subsequently altering regional climate regimes in the Northern Hemisphere (Overland and Wang 2010; Budikova 2009).

This paper reviews a targeted selection of the relevant literature published in 2009 and early 2010. The scope of this review is limited to the unidirectional impacts of sea ice upon climate; neither the climatological forcings on sea ice nor the numerous known ice–atmosphere feedback mechanisms inherent to the system are considered here. I begin with an overview of the physical processes by which sea ice–atmosphere interactions occur and follow with a synopsis of the observed and expected regional climate impacts of decreasing sea ice. Finally, I discuss the potential utility of summer sea ice extent as a predictive tool for intra-annual climate forecasting.

2. Physical Mechanisms

Arctic sea ice has long been known to have a meaningful impact on both local and geographically remote climate regimes. Observational studies as far back as the early 1900s demonstrate a correlation between winter conditions and the extent of sea ice during the antecedent summer (Budikova 2009). In intervening decades, research has rigorously established the *causative* nature of the relationship between sea ice and Northern Hemisphere climate, providing insight into the radiative and dynamical processes by which these interactions take place.

a. Radiative and thermal processes

As sea ice decreases, increasingly large areas of open water (or low ice concentration) develop in previously ice-covered regions. The increasing ratio of open water to sea ice decreases the local surface albedo and leads to major changes in regional radiative equilibrium. A much larger fraction of downwelling shortwave solar radiation is absorbed at the ocean surface, and sea surface temperatures increase accordingly (Deser et al. 2010). The Arctic Ocean tends to act as a heat sink through most of the summer months, releasing its stored energy near the end of the annual melt season in September and October (Deser et al. 2010). Some of this excess thermal energy is transported via ocean currents to lower-latitude marine basins, and the rest is transferred to the lower atmosphere through conduction and convection within the boundary layer (Budikova 2009). Thus, positive oceanic heat flux anomalies induced by reductions in sea ice ultimately lead to increased local air temperatures in the Arctic.

b. Dynamical processes

Anomalous surface heating tends to increase the height of the lower troposphere, leading to greater geopotential thicknesses as the vertical mean temperature rises. In addition to altering local wind patterns in the Arctic, increasing polar thicknesses weaken the meridional geopotential gradient. Because the prevailing westerlies are driven by this latitudinal gradient, decreasing sea ice leads to weakening and southward shift of the mid-latitude jet stream. Changes in the spatial distribution of geopotential thicknesses—and subsequent sea level pressure (SLP) anomalies—also affect the initiation and propagation of large-scale planetary (Rossby) waves (Budikova 2009). On a smaller spatial scale, there is greater consensus that warmer temperatures in the Arctic do increase baroclinic instability near the ice margin and lead to stronger local cyclonic storm activity, some of which may propagate to lower latitudes (Budikova 2009).

3. Regional Climate Impacts

Dramatic sea ice loss has occurred within the past decade, and especially within the past five years (Budikova 2009). This has afforded researchers the rather unprecedented opportunity to observe in near real-time the atmospheric response to actual sea ice forcing (Overland and Wang 2010). These observations may prove useful in verifying numerical model predictions of climate sensitivity to future sea ice conditions.

a. Observed impacts

Weakened mid-latitude westerlies in the middle latitudes have led to a decrease in the intensity of storms, namely at latitudes above 45°N. Despite this overall decrease in storminess, however, observed precipitation at middle latitudes has increased in years experiencing anomalously low winter sea ice conditions. Storm tracks have been observed to shift southward over the continental landmasses during winter (especially North America), but northward over the oceans (Budikova 2009). This shift is part of a wider trend towards amplified meridional flow as sea ice decreases, as evidenced by a notable negative trend in the North Atlantic Oscillation (NAO) during winter (Overland and Wang 2010). Observable impacts include outbreaks of cold air in winter over land areas and significant poleward warm advection over the oceans (Overland and Wang 2010; Budikova 2009). Additionally, high pressure regions over both the subtropical Pacific and Atlantic ocean basins have been displaced from climatologically-favored positions (Budikova 2009).

As noted previously, dramatic changes in Arctic storm intensity and track have been noted (Budikova 2009). Lower-tropospheric temperature anomalies in recent years have been very large (Fig. 1); late autumn anomalies in the central and Pacific Arctic increased from +2°C in 1995 to +6°C in 2007–2008 (Overland and Wang 2010). The magnitude of temperature anomalies resulting from sea ice loss is greatest in the Arctic, but significant anomalies can propagate over 1,000 km via advective and turbulent mixing processes (Budikova 2009). Though there is little doubt that significant positive temperature anomalies are present, confidence in the magnitude of Arctic air temperature anomalies is limited by the paucity of reliable surface observations over much of the Arctic, particularly near the pole (Overland and Wang 2009). I suggest that increasing marine traffic in the Arctic may present an opportunity to close this observational gap and establish a more reliable local surface temperature record through ship-based radiosonde launches or simple surface observations.

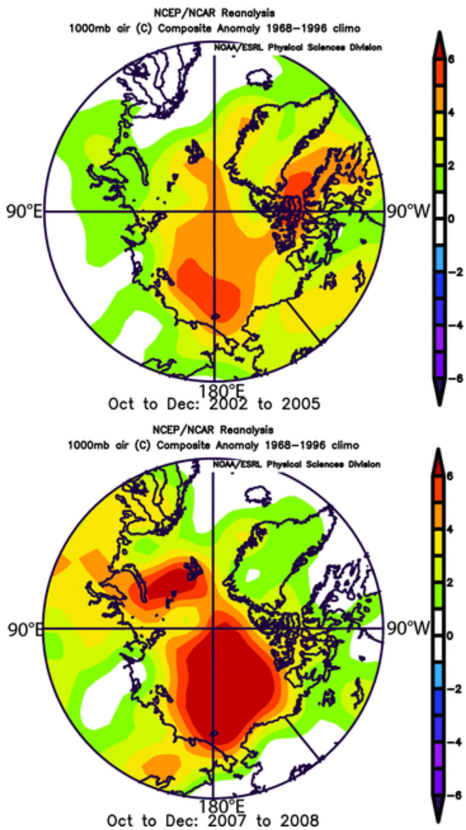

Fig. 1. Lower-tropospheric temperature anomalies (°C) in the Arctic for October–December 2002–2005 (top) and October–December 2007–2008 (bottom). Adapted from Overland and Wang (2010) *Tellus Series A: Dynamic Meteorology and Oceanography* 62A. © John Wiley and Sons. Reprinted with permission.

b. Projected impacts

Sea ice loss to date has been much more rapid than predicted by most coupled global climate models (GCMs), especially since 2007 (Overland and Wang 2010). Natural variability and the action of positive feedbacks in the ice–ocean–atmosphere system are implicated as principal causes of this discrepancy (Budikova 2009). The potential for positive feedback in any Arctic system forced by climate is not negligible, and further investigation into the qualitative and directional nature of such feedback is critical to a holistic understanding of the sea ice–atmosphere system. Extensive discussion of these effects, however, is beyond the scope of this paper.

To circumvent the complication of feedback mechanisms and determine the sensitivity of the general atmospheric circulation to sea ice conditions alone, Deser et al. (2010) used a prescribed set of estimated future sea ice conditions and observed sea surface temperature values from the 1980–1999 period to simulate climate in an uncoupled GCM. Results from this study indicate that a fundamental restructuring of the high-latitude troposphere may occur once seasonally ice-free conditions become established in the Arctic. The present-day 10°C surface temperature inversion over the Arctic Ocean disappears entirely in the model,

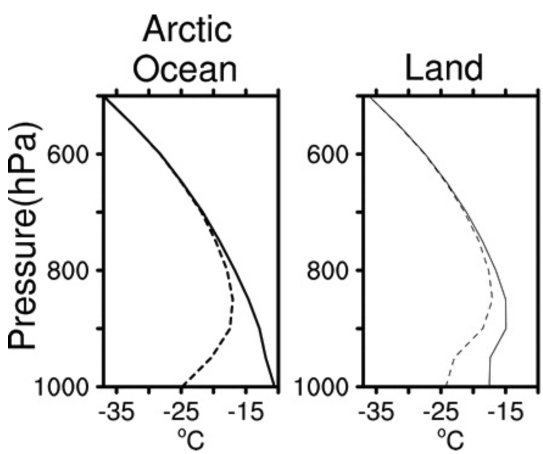

Fig. 2. Vertical atmospheric temperature profiles for 1980–1999 (dashed curves) and 2080–2099 (solid curves) over Arctic Ocean (left) and high-latitude continental areas (right). Adapted from Deser et al. (2010) *Journal of Climate* 23: 333–351. © American Meteorological Society. Reprinted with permission.

allowing the boundary layer to destabilize (Fig. 2). Deser et al. note surface warming as great as 16°C over water and 6.5°C over land, in addition to widespread changes in precipitation (mostly positive anomalies) poleward of 45°N. Geopotential height anomalies—apparently driven by surface heat flux anomalies—are especially pronounced in the winter months. Interestingly, Deser et al. (2010) do find in the model output an increased instance of negative "NAO-like" conditions, which is in agreement with the research of Seierstad et al. (2009) and the publications reviewed by Budikova (2009). That Overland and Wang (2010) have actually observed an increased NAO-negative response to sea ice reductions lends considerable credence to this particular aspect of the model predictions and does perhaps signal the potential for such knowledge to be used in an interseasonal predictive setting.

Using a similar GCM methodology to Deser et al. (2010), Seierstad and Bader (2009) project a significant reduction in mid-latitude winter storm activity (mainly in December and January). The aforementioned NAO-negative response is most apparent in the month of March, though it does appear to a lesser degree throughout the winter (Seierstad and Bader 2009). Ultimately, these model projections correspond well to presently observed trends (note especially Overland and Wang 2010). Because the projections of Deser et al. (2010) and Seierstad and Bader (2009) are based on sea ice projections made for years between 2030 and 2099, however, such agreement between projection and observation reinforces the consensus view that the present rate of sea ice decline is far greater than had been expected. As such, the potential future impacts described in these studies may become relevant at a much earlier date than explicitly projected.

4. Sea Ice Conditions As an Intra-Annual Predictive Tool?

The results of Overland and Wang (2010) and others do indicate a distinct linkage between recent early autumn sea ice conditions and meteorologically observable trends during the following winter season. If such linkage is robust and evolves in a predictable manner with respect to *changes* in sea ice conditions through time—as appears to be the case—the possibility exists that summer sea ice extent could be used as a relatively long-lead indicator for Northern Hemisphere climate patterns on time scales of less than one year. Particularly intriguing is the noted correlation between a negative "NAO-like" signal in both real and modeled scenarios (Overland and Wang 2010; Seierstad and Bader 2009). Since the NAO is already used extensively in operational climate prediction as a teleconnection index, advance knowledge of its likely behavior in a given year would be of almost immediate utility.

Two caveats, however, do require special consideration. First, Seierstad and Bader (2009) find that the sea ice–forced NAO signal is strongest in March and has much lower amplitude in other calendar months. Though this study was limited in scope and involved a single GCM, further research should be conducted to determine whether sea ice does indeed force the amplitude of the NAO to a greater extent during certain subseasonal intervals. Secondly, the linearity of the climate response to sea ice forcing will be a crucial aspect of any predictive index that is developed. Budikova (2009) and Overland and Wang (2010) point out that the direct (baroclinic) effects of sea ice forcing on climate are largely linear, but that significant indirect effects (such as the barotropic contribution to SLP fields) are not. Caution, therefore, is advisable if attempting to use previous-summer sea ice extent as a climate predictive tool, though the associated uncertainties may well diminish as additional observational data become available in future years.

5. Summary and Conclusions

That dramatic shifts in Arctic sea ice conditions have occurred in the past decade is unequivocal (Budikova 2009). An increasing body of evidence strongly indicates that these reductions in sea ice extent have forced significant changes in the general atmospheric circulation and climate of the Northern Hemisphere (Budikova 2009; Overland and Wang 2010). The physical mechanisms that drive sea ice–atmosphere interactions are relatively well understood, but uncertainties are still sufficient to prevent a high-confidence forecast regarding the future evolution of the sea ice–climate system (Deser et al. 2010; Seierstad and Bader 2009; Overland and Wang 2010). All indications, however, do point to the continued amplification of climate impacts in the Northern Hemisphere as Arctic sea ice declines at an unprecedented rate (Budikova 2009; Deser et al. 2010). Finally, the potential to use summer sea ice conditions in an intra-annual climate predictive capacity is highly promising and should be studied further. The observed acceleration of Arctic sea ice loss over the past decade and its subsequent impacts on climate highlight the urgency of ongoing research to better understand the complex relationship between sea ice and the atmosphere.

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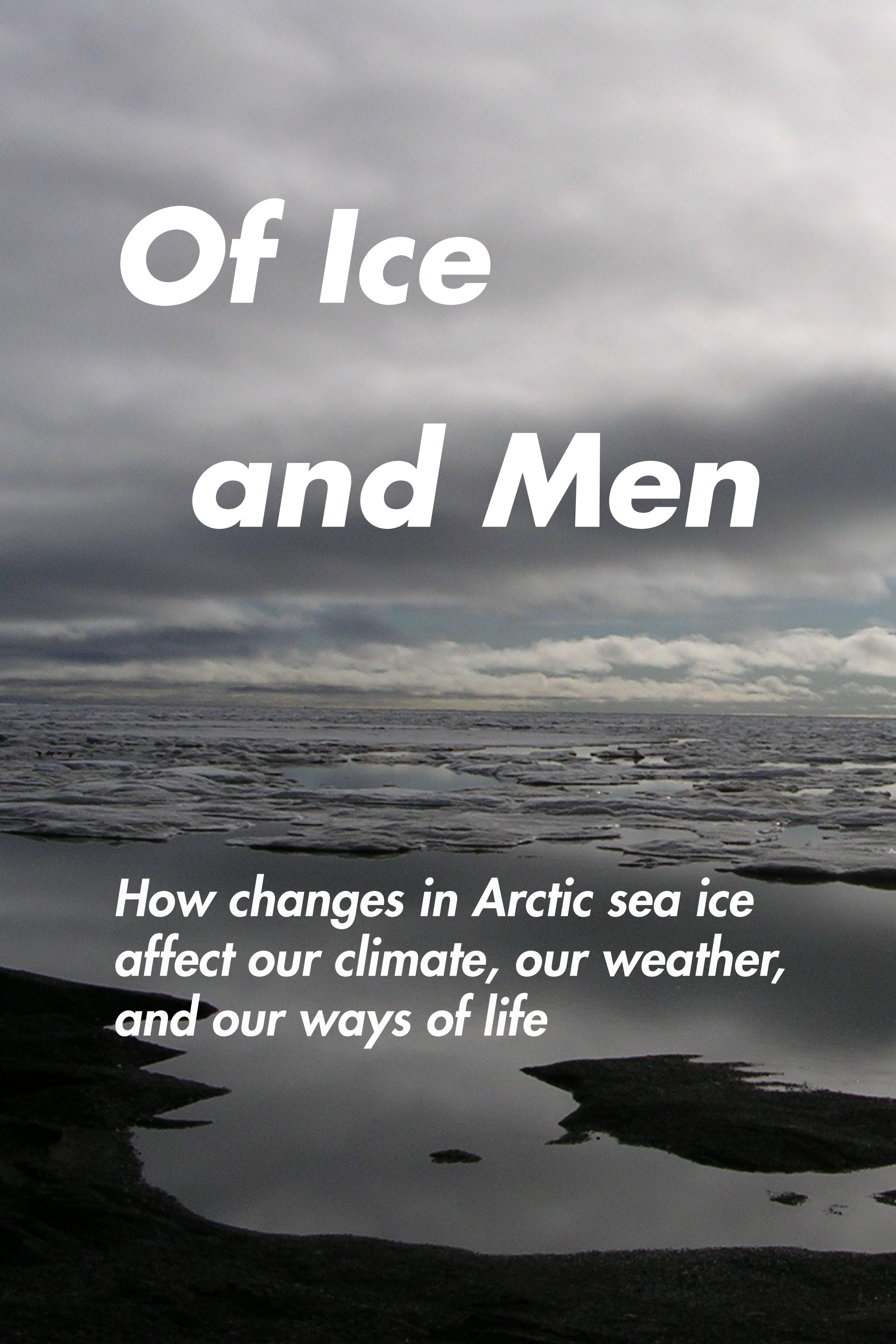


Of Ice and Men

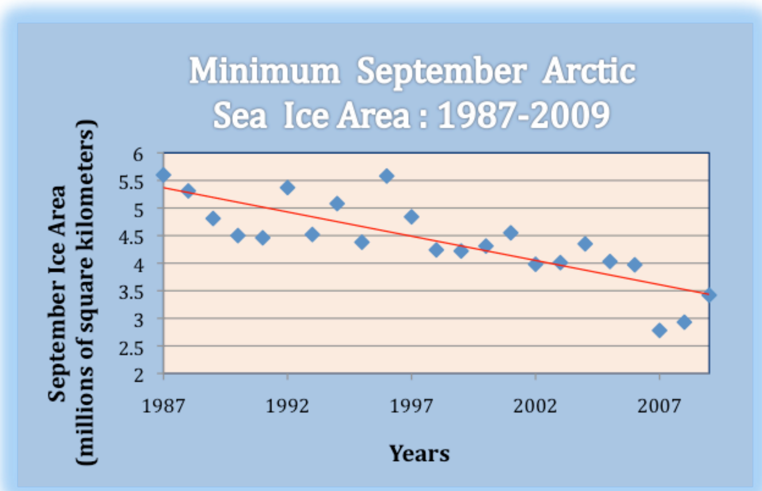
How changes in Arctic sea ice affect our climate, our weather, and our ways of life

The Chukchi Sea near Barrow, Alaska, June 2007. Photograph by Linda LaMond.

The temperature was a balmy thirty-five degrees Fahrenheit, and a refreshing twenty-mile-per-hour seabreeze was blowing off the Arctic Ocean under brilliantly sunny June skies when I first arrived at the Wiley Post–Will Rogers Memorial Airport in Barrow, Alaska. The three-hour flight from Fairbanks had been something of an adventure in itself—I had shared the converted 737 with oil workers, grizzled Alaskan old-timers, several thousand cans of Coca Cola, and a fairly large piece of earthmoving equipment while the pilot circled the Deadhorse airport waiting for a herd of caribou to clear the runway—but it was only after I stepped out onto the dusty dirt road outside of the one-room airport in Barrow that I realized how unusual this isolated settlement truly was.

A city of less than five thousand souls in the Alaskan Arctic, Barrow lies near the confluence of the Chukchi and Beaufort Seas and is the northernmost inhabited place in the United States. The climate is extremely harsh—the Arctic coast region is a desert, receiving less than five inches of precipitation each year—and annual average temperatures are among the lowest in Alaska. Due to Barrow's high latitude, the sun does not rise above the horizon for over two months in the dead of winter.

Day-to-day life here is dictated largely by the weather and the icy ocean to the north, and for those who depend on sustenance fishing or whaling (not uncommon among Iñupiat residents), the annual summer



melting of the frozen ocean is a much anticipated event. In recent years, though, this local milestone has been occurring much earlier in the season—and far less predictably—than in the past. And changes in the behavior of Arctic sea ice have not been relegated merely to the Alaskan coast: all across the Arctic Ocean basin, ice melt has been increasing and aerial extent of ice decreasing at an alarming rate. As dramatic as the local consequences of melting sea ice appear to be, however, the implications for those of us at lower latitudes—in the form of changing weather patterns—may prove to be even more troubling.

A Precipitous Decline

Seasonal fluctuation of Arctic sea ice is not a new phenomenon. Each year, relatively warm summer temperatures and southerly winds act to break up the solid mass of sea ice that in colder months extends continuously between the far northern margins of North America, Europe, and Asia. The edge of the ice retreats to the north, and the overall area of ocean covered by ice decreases substantially. Large expanses of broken sea ice coverage remain throughout the summer, and even during the warmest part of the year such discontinuous areas of ice may temporarily impinge on coastal areas well to the south of the main ice edge as transitory weather patterns bring shifting wind currents. Summer melting almost always reaches its peak in September, and a rapid freeze-up usually occurs soon thereafter as much colder temperatures return to the Arctic in October.

> ***Since 1979, minimum September sea ice area has decreased at an average rate of 72,000 square kilometers each year—an area nearly the size of the state of Georgia.***

Since reliable satellite observations of sea ice extent began in 1979, however, a steady trend towards increased summer melting and less sea ice overall has been documented. According to the National Sea Ice Data Center (NSIDC), minimum September ice area has decreased at an average rate of 72,000 square kilometers *each year*—an area nearly the size of the state of Georgia. Aerial extent of winter sea ice has been decreasing at a lesser (though still notable) rate.

Of course, you don't need to convince the denizens of Barrow that sea ice conditions are changing rapidly. Out on the black sand beach adjacent to a row of homes and small business in the northwestern part of town, I was approached by a town councilman who was more than willing to make known his own observations regarding the ice, the climate, and the local way of life. Powerful storms, he told me, had been eating away at the shoreline as ocean swells crashed ashore where solid ice once held fast, and buildings were succumbing to the erosion. Polar bears, caught off guard by the unusually early retreat of the sea ice, were wandering into town looking for food and disrupting the traditional whale harvest. "Just look," he said grimly, motioning his hand in the direction of the nearly ice-free ocean several yards to our north. His concerns were by no means unique—later that same day, I spoke with a couple who repeated many of the same worries and in addition voiced concerns that the disappearing sea ice would make ship transportation more feasible and lead to increased commercial development.

Track changing sea ice
in real time via the NSIDC website:
http://nsidc.org/arcticseaicenews

It quickly dawns on one, as a visitor in the Alaskan Arctic, that the changes in sea ice are forever altering the state of the entire region and have already affected the quality of life and daily routines of those who live there. The question, however, still remains: how do seasonal reductions in sea ice affect weather conditions in the rest of the world?

An Icy Relationship

The interaction between sea ice and climate, it turns out, is a two-way street. It may seem obvious that warming temperatures in the Arctic lead to ice melting, but the flip side of the paradigm—whereby decreasing sea ice leads to changes in climate—can be more difficult to visualize. Normally, sea ice has a high albedo (or reflectivity), which allows a significant portion of the solar radiation reaching the ocean to bounce back into the atmosphere without causing warming at the surface. Where sea ice is patchy in coverage, however, areas of open water are exposed directly to the incoming solar radiation. Since water is "darker" than ice and absorbs a larger fraction of the radiation, local water temperatures become warm relative to what they would have been in the presence of solid ice. Even in regions where the ice is solid, pools of melt water form on top of the existing surface and help to accelerate the overall melting process.

All of this extra warmth is transferred to the air via conduction, which ultimately leads to a warming of the lower atmosphere. This warming effect is further amplified if sea ice disappears completely from a given region, as regularly occurs over much of the Arctic Ocean during the warm season. As the average global temperature increases as a result of climate change, these areas of open water have become larger and appeared in new geographic regions, and the warming of the atmosphere has accelerated.

The cumulative effect of this localized Arctic warming is ultimately felt very far from the source. Because the weather on our planet is driven primarily by nature's tendency to equalize the substantial temperature difference between the equator and the poles, a temperature change in either of these regions would act to substantially alter the global heat pump that is our climate. Though temperatures have been increasing in both polar and equatorial regions, the rate of increase has been much greater at high latitudes. The increased rate of warming in the far north has been attributed (in large part) to the effects of melting sea ice. Since temperature increases in the colder high latitudes are outpacing those in warmer tropical regions, the overall temperature difference (known as the meridional temperature gradient) is *decreasing*. As this gradient weakens, so do the high-altitude westerly winds that encircle the globe. The most intense band of these winds, commonly referred to as the jet stream, defines the path and affects the intensity of storm systems as they travel though the mid-latitudes. At the same time, local temperature anomalies in the Arctic that occur on account of sea ice melting drive an *increase* in the horizontal temperature gradient, which serves to strengthen north–south winds. Ultimately, the changing strength, position, and direction of the jet stream leads to noticeable changes in day-to-day weather across the Northern Hemisphere.

The cumulative effect of "localized" Arctic warming is ultimately felt very far from the source in the form of shifting weather patterns.

A Slippery Slope

Especially startling has been the rate at which such changes have taken place. The Arctic experienced an unprecedented summer melt season in 2007, obliterating all-time records for minimum sea ice extent. The atmosphere appeared to respond quite rapidly to this tremendous ice loss: the late fall and early winter of 2007–2008 brought highly anomalous wind and temperature patterns to nearly all of the Arctic and much of the Northern Hemisphere. While ice loss in the two intervening years has not been quite as dramatic, the strong downward trend in both seasonal ice minima and annual ice coverage has continued.

In the midst of a winter that brought both a "Snowpocalypse" and "Snowmageddon" to the U.S. Eastern Seaboard and has thus far been bitterly cold across much of the North American and European continents, it may be hard for some to take seriously the threat posed by the ongoing loss of Arctic sea ice. But there are strong indications that weather patterns such as these—in which cold Arctic air is forced unusually far to the south—are similar to what would occur in response to a significant loss of sea ice during the preceding melt season. And, as it turns out, strong northerly winds over the Arctic—especially when they occur during the summer months—have a tendency to "flush" remaining sea ice out of the Arctic basin, further accelerating ice loss and curtailing re-freezing in subsequent winters. Nature is no foe of irony, and a number of recent studies have shown that counterintuitive effects such as these may well become more common as the global climate continues to shift.

An Ice-Free Future

When I left Barrow in June of 2007, I was unaware of the extraordinary changes that would take place in the months to come. Even the world's foremost experts were caught off guard: the ice melt observed during 2007 was so great that it exceeded even the most pessimistic computer model forecasts that had previously been made. More recent predictions have taken into account the increasingly rapid rate of ice loss and now call for the appearance for a seasonally ice-free Arctic Ocean by as soon as 2030. Should such predictions prove to be even close to reality, further dramatic changes in Northern Hemisphere climate could become reality.

Despite appearances, change comes quickly to Barrow. In 2007, I heard rumblings about the possibility of offshore oil exploration in the

Beaufort Sea, made possible in part by the decreasing summer sea ice. By late 2009, a petition by Shell Oil to begin drilling had been approved by the Department of the Interior, and work is slated to begin in Summer 2010. It is worth noting—from a darkly humorous point of view—that the extremely long duration of ice-free seas in 2007 likely played a significant role in the decision to proceed with drilling. In 2008, the U.S. Coast Guard announced its intention to establish a permanent presence in Barrow on account of dramatically increasing ship traffic (this in a region which as recently as a decade ago was rarely traversed except by ice-breaking vessels). Residents continue to fight tooth and nail to preserve their traditional way of life, but environmental and related economic forces appear to be winning the battle. The rest of us should view the present situation in the Arctic as an early warning signal rather than a cautionary tale. As summer ice is replaced by vast expanses of open water and global weather patterns shift in response, the changes wrought by Arctic climate change profoundly affect people at all latitudes. It's a process we've already set in motion, and we're all along for the ride.