Correlated Declines in Pacific Arctic Snow and Sea Ice Cover

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Simulations of future climate suggest that global warming will reduce Arctic snow and ice cover, resulting in decreased surface albedo (reflectivity). Lowering of the surface albedo leads to further warming by increasing solar absorption at the surface. This phenomenon is referred to as "temperature–albedo feedback." Anticipation of such a feedback is one reason why scientists look to the Arctic for early indications of global warming.

Much of the Arctic has warmed significantly. Northern Hemisphere snow cover has decreased, and sea ice has diminished in area and thickness. As reported in the Arctic Climate Impact Assessment in 2004, the trends are considered to be outside the range of natural variability, implicating global warming as an underlying cause. Changing climatic conditions in the high northern latitudes have influenced biogeochemical cycles on a broad scale. Warming has already affected the sea ice, the tundra, the plants, the animals, and the indigenous populations that depend on them.

Changing annual cycles of snow and sea ice also affect sources and sinks of important greenhouse gases (such as carbon dioxide and methane), further complicating feedbacks involving the global budgets of these important constituents. For instance, thawing permafrost increases the extent of tundra wetlands and lakes, releasing greater amounts of methane into the atmosphere. Variable sea ice cover may affect the hemispheric carbon budget by altering the ocean–atmosphere exchange of carbon dioxide. There is growing concern that amplification of global warming in the Arctic will have far-reaching effects on lower-latitude climate through these feedback mechanisms. Despite the diverse and convincing observational evidence that the Arctic environment is changing, it remains unclear whether these changes are anthropogenically forced or result from natural variations of the climate system. A better understanding of what controls the seasonal distributions of snow and ice is fundamental to the problem.

Why Be Concerned? The Temperature–Albedo Effect

Anticipation of a temperature–albedo feedback is the primary reason observers look to polar regions for early indications of global warming. This effect relates to the dramatic contrast in the reflectivity of sunlight by snow or ice compared with open tundra or seawater. Fresh snow reflects up to 90% of incoming solar radiation, while tundra and open water reflect only 15–20% and 6–8%, respectively. Changes in albedo affect the net energy balance at the surface, which in turn influences air temperature. An increase in net energy can raise temperatures, depending on how that energy is redistributed. Most of the excess energy is stored in the ground initially but is released as heat over time to warm the air above.

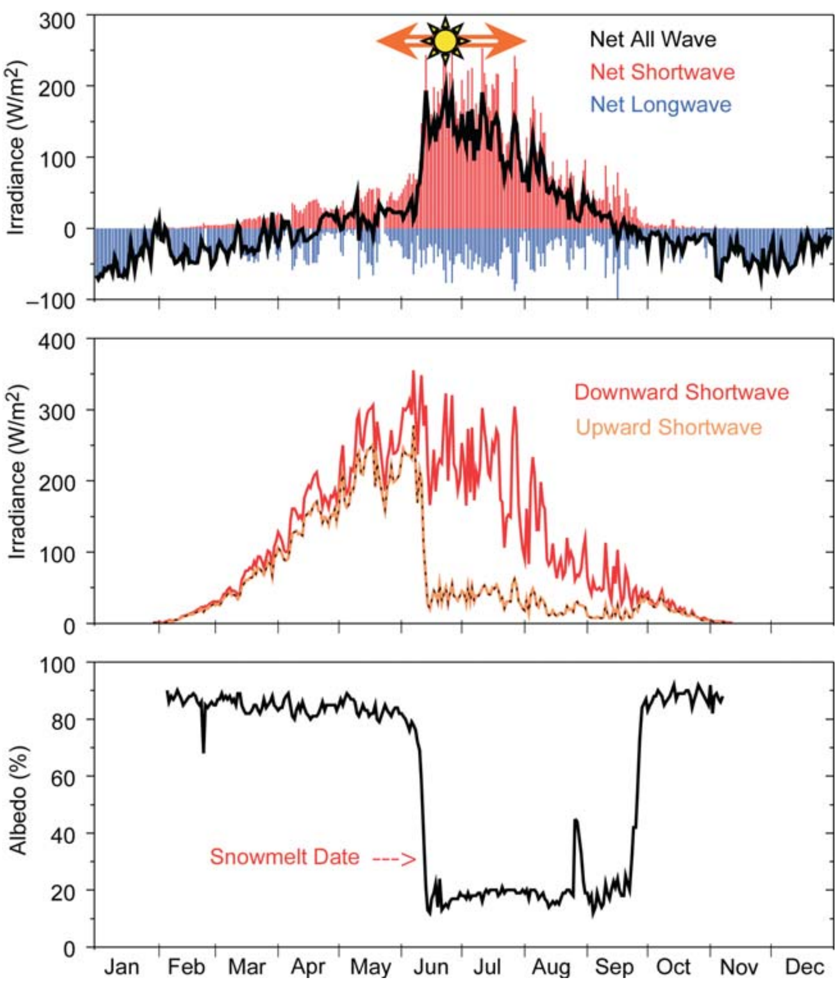
It has been rightfully stated that "the most significant factor influencing the magnitude of the yearly net radiation total is the date when snowmelt is completed."* The timing of snow and ice melt over vast regions of the Arctic can affect climate on a hemispheric scale. Thus, it is important to monitor changes in Arctic snow and sea ice cover and understand what causes them to vary.

Earlier Snowmelt in Northern Alaska

Since 1940 the spring melt at the NOAA/CMDL Barrow Observatory (BRW) has advanced by about 10 days. Most of the advance occurred after 1976, however. The break in the record coincides with regime shifts in many climatic and biological indicators of change, mainly a consequence of

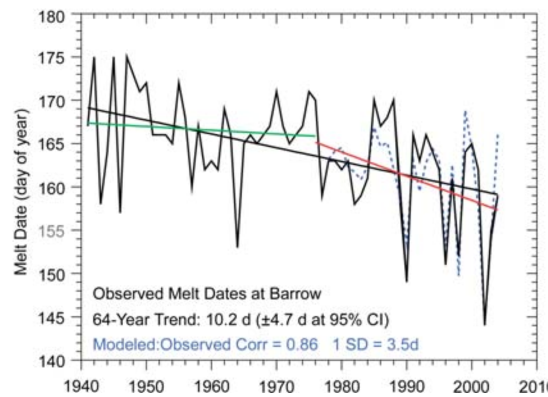
* Maykut, G.A., and P.E. Church (1973) Radiation climate of Barrow, Alaska. *Journal of Applied Meteorology*, Vol. 12, p. 620–628.

changing atmospheric circulation patterns in the North Pacific. The year 2002 had a record early melt. The 2003 melt was again early, followed by a moderately early melt in 2004. The past three years, when combined with 1990, 1996, and 1998, are unprecedented in the 64-year record. These anomalously early events statistically drive the long-term trend.



Annual cycles of daily average radiative energy at the NOAA/CMDL Barrow Observatory (BRW). The surface albedo (the bottom panel) is the ratio of the upwelling to the downwelling shortwave irradiance (middle panel), where irradiance is a measure of solar energy. Historically, a daily average albedo threshold of 30% is used to define the final day of snowmelt at BRW; i.e., when the snow cover essentially disappears. During the final week of melting, the albedo falls rapidly from about 75% to about 17%. The impact that this change has on the net all-wave radiative energy balance is illustrated in the top panel, where net all-wave radiation is simply the sum of the net shortwave and longwave components. Values of net short- and longwave irradiance are determined as downward minus upward components, indicated by red and blue spikes in the top panel. The dramatic decrease in albedo at the time of snowmelt results in a large increase in the net radiative energy (black curve) because of increased solar absorption by the surface. In this example, the rise can be likened to illuminating every square meter of the tundra by a 120-watt light bulb (net irradiance increases by about 120 W m^{-2}). Even more dramatic increases will occur over ocean areas, because seawater has a lower albedo than tundra. It is because the melt season coincides with the peak of the annual solar cycle that the albedo effect is so large.

Variations in the annual snow cycle of northern Alaska are attributable, in large part, to changes in atmospheric circulation related to the position and intensity of two pressure systems: the Aleutian Low (AL) and the Beaufort Sea Anticyclone (BSA). On this basis, an empirical model was developed to predict melt dates at BRW. About 75% of the interannual variability in snowmelt dates at BRW is explained by the model's input parameters: changes in snowfall during winter and variations in springtime temperatures and cloudiness.

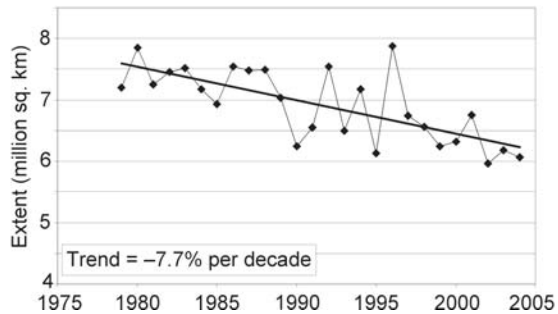


Time series of snowmelt dates (as day of year) constructed for the NOAA/CMDL Barrow Observatory. Three linear regressions are plotted: an overall fit for 1941–2004 (thin black line), one for all years prior to 1977 (green), and a third beginning in 1977 (red). The results of an empirical model are also shown (dashed blue line). The time series was compiled from direct snow depth observations, proxy estimates using daily temperature records, and, beginning in 1986, surface albedo measurements.

The timing of snowmelt perturbs the net surface energy budget through the albedo effect. Using continuous radiometric measurements made at BRW, the effect can be quantified. A 10-day advance in snowmelt results in a 14–16% increase in net surface radiative energy during the season, equivalent to more than 2 W/m^2 of thermal forcing on an annual basis. While this sounds like a small perturbation, an increase of only 1.0 W/m^2 in net surface radiation can increase the air temperature by more than 0.5°C. The additional energy is redistributed in complicated ways that involve ground storage, sensible and latent heat exchanges between the surface and atmosphere, and air flow that distributes the energy gain to other regions. In addition to contributing to warming, the recent thawing of permafrost in the region is probably attributable in large part to earlier snowmelt. Many biogeochemical cycles are also influenced by the length of the growing, or snow-free, season at high latitudes.

Diminishing Sea Ice in the Western Arctic Ocean

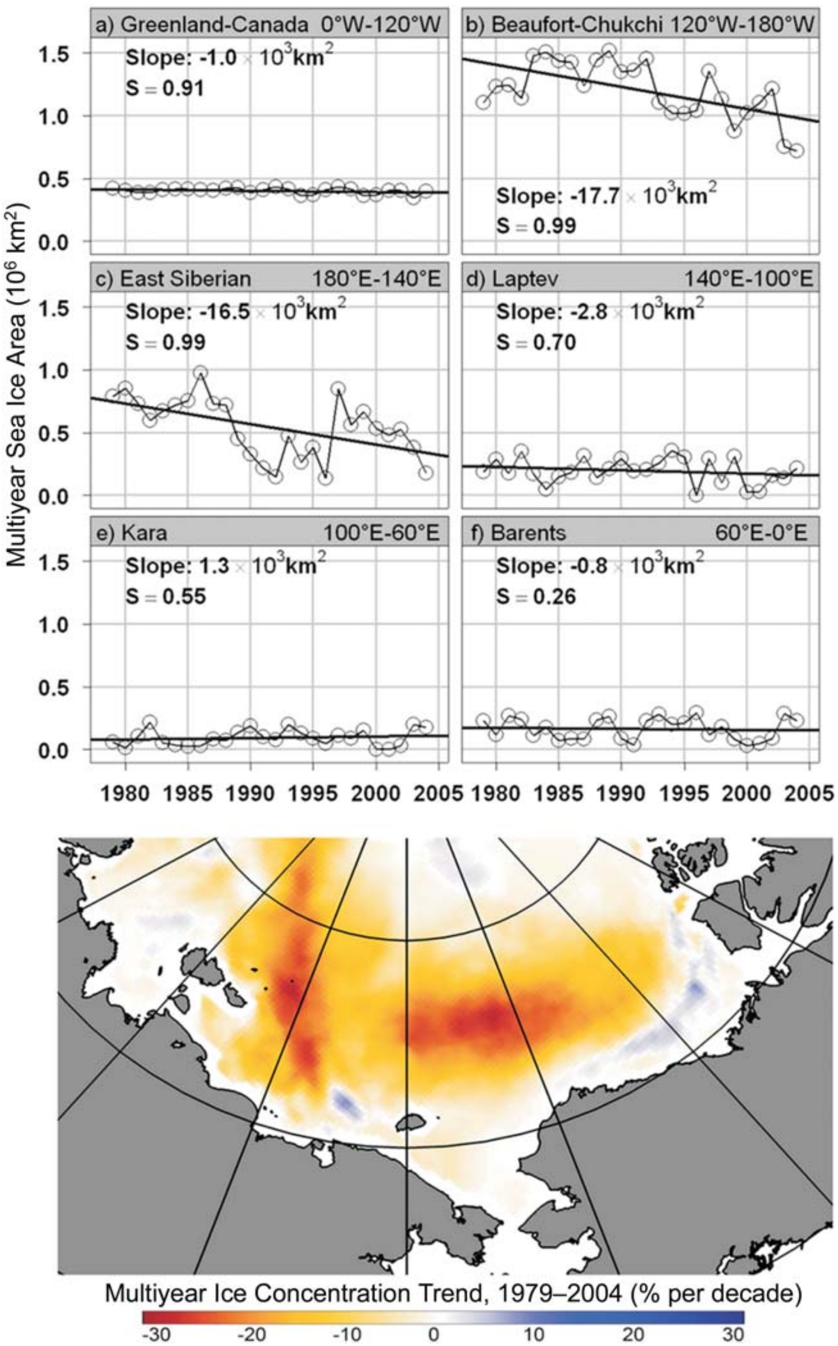
One of the most alarming indicators of global climate change is the continuing decline of Arctic sea ice. Sea ice distributions have been tracked historically by direct observations from ship and aircraft and since the late 1970s from satellite platforms. Passive microwave (PMW) satellite sensors provide daily data for evaluating sea ice conditions, including surface melt, age, ice concentration, and derived extents. From such analyses we know that the maximum retreat (or minimum extent) of ice occurs in September each year. Since the late 1970s, September sea ice extent has decreased by nearly 20%. The minimum occurred in 2002, coincident with the record early snowmelt in northern Alaska. Last year (2004) marked the third consecutive year of anomalously extreme ice retreat in the Arctic.



Time series and linear trend in September Arctic sea ice extent, 1979–2004. The calculation is made for areas having an ice concentration greater than 15.0%. The regression yields a decrease of about 7.7% per decade.

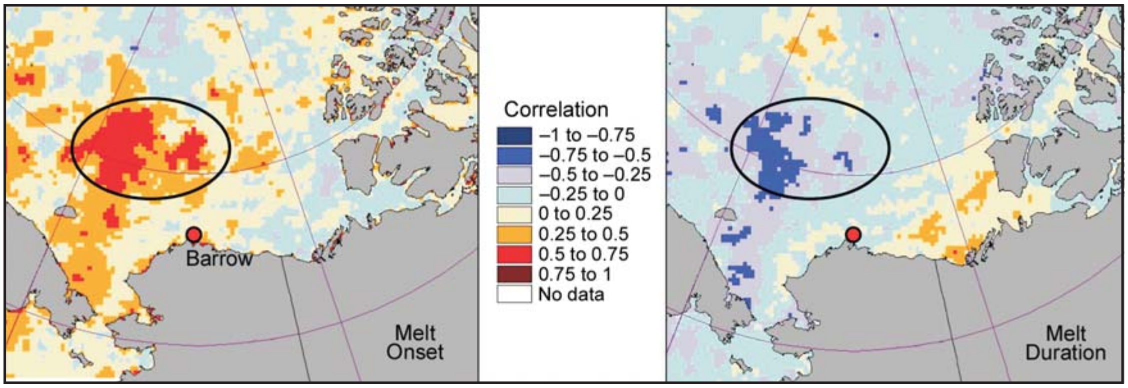
As a consequence of accelerated warming at high latitudes caused by the temperature–albedo effect, some climate simulations predict ice-free summers in the Arctic by the end of this century. Even approaching this scenario will gravely affect Arctic ecology. The zooplankton, fish, and marine mammals that depend on perennial sea ice, such as polar bears and a variety of seals, will be directly impacted.

Although differing explanations are given for the decline in Arctic sea ice, there is consensus that patterns of change derived from satellite PMW data are qualitatively reliable. As in the case of snowmelt at BRW, since 1989 several anomalous years drive the overall decline in ice extent. Changes in multiyear ice (MYI), which is sea ice that has survived at least one summer melt season, have varied geographically. Since 1979, MYI has decreased by more than 60% over large areas of the western Arctic Ocean. The most pronounced decline began in 1989 in the east Siberian region, followed a few years later by an area north of Alaska in the Beaufort–Chukchi region. After a rebound in 1997, the downward trend resumed. These dramatic declines in the Pacific Arctic dominate the trends for the entire basin.



Interannual changes and trends in January multiyear ice area within six longitudinal sectors of the Arctic Ocean (top), and 26-year (1979–2004) linear trend in January multiyear ice concentrations within the western Arctic (bottom).

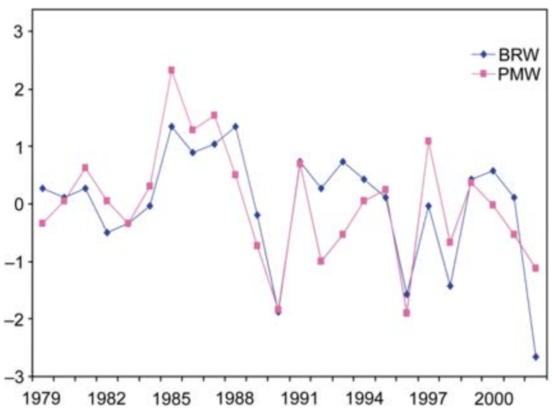
Maps contouring correlation coefficients between the date of snowmelt at the NOAA/CMDL Barrow Observatory (indicated by the red dot) and the onset date of snowmelt over sea ice (left) and the melt season duration (days) over sea ice (right). The circles indicate an area of high correlation.



Correlations of Melt at Sea and on Land

The snowmelt at BRW and the sea ice trends in the Pacific Arctic appear to be related. The relationship is made clearer through cross-correlations between time series of melt onset dates over sea ice and snowmelt dates at BRW. A large region of high positive correlation exists between melt onset over sea ice and the BRW melt record. Much of this region also experiences a longer duration of melt.

Time series of standardized anomalies of BRW melt dates (blue) and a small area of melt onset over ice (pink) located within the region of high correlation. Standardization normalizes interannual variations to a common scale to facilitate comparisons.



To better visualize these results on a scale of equal variance, standardized anomalies (normalized differences) were computed for each time series. The results demonstrate that anomalous melt onset dates over sea ice in the Chukchi–Beaufort region are reflected by similar anomalies in the snowmelt dates at BRW.

Factors that Influence Snow and Sea Ice Distribution

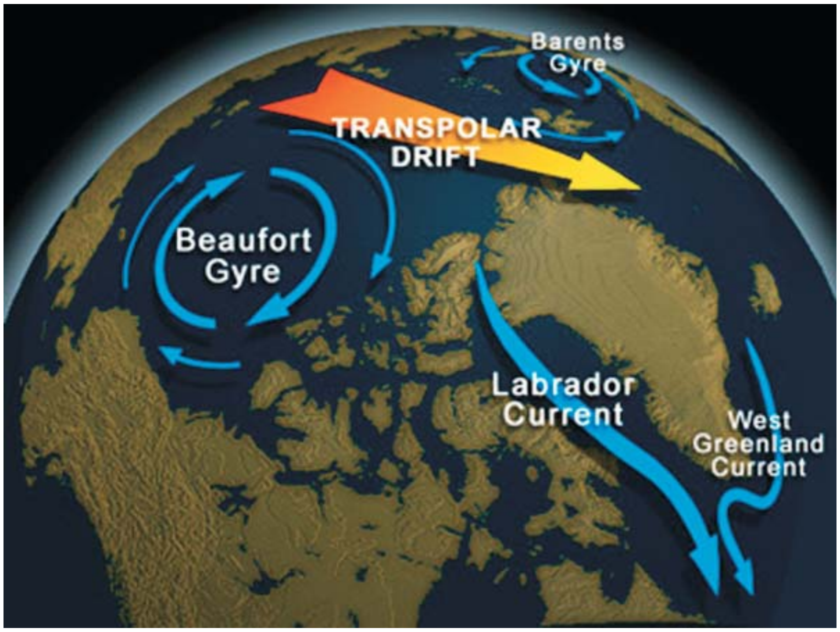
The fact that melt chronologies over land and at sea have co-varied for many years over a large region suggests linkages to common physical forcing mechanisms. Several processes could underlie these variations, including changes in atmospheric dynamics, synoptic-scale patterns, and related effects.

Atmospheric Dynamics

There is general consensus that the overall decline in Arctic sea ice (since the late 1970s) is due to processes associated with dynamical changes in the atmosphere. On a pan-Arctic scale, the dynamical state of the atmosphere is often expressed in terms of an Arctic Oscillation (AO) index that relates to sea-level pressure variations. High indices indicate lower-than-average sea-level pressure over the central Arctic. During a recent and predominately positive phase of the AO (1989–1995), MYI concentrations declined rapidly in a broad region of the western Arctic Ocean. It is hypothesized that during these years the Beaufort Gyre, a region of recirculating ice north of Alaska, weakened. The weakened gyre allowed more ice to become entrained in a dominant current called the Transpolar Drift Stream, which exports sea ice into the North Atlantic east of Greenland. The thick multiyear ice that was exported was replaced by younger, thinner ice that is more vulnerable to melting during the summer months. In recent years the AO index has been neutral or negative, however, and sea ice continues to decline. This suggests that factors not well represented by the phase of the AO are at play. Below, an examination of environmental conditions during years of anomalous ice retreat reveals+ how regional circulation patterns contribute to observed snow and ice variations in the Pacific Arctic.

Synoptic-Scale Influences

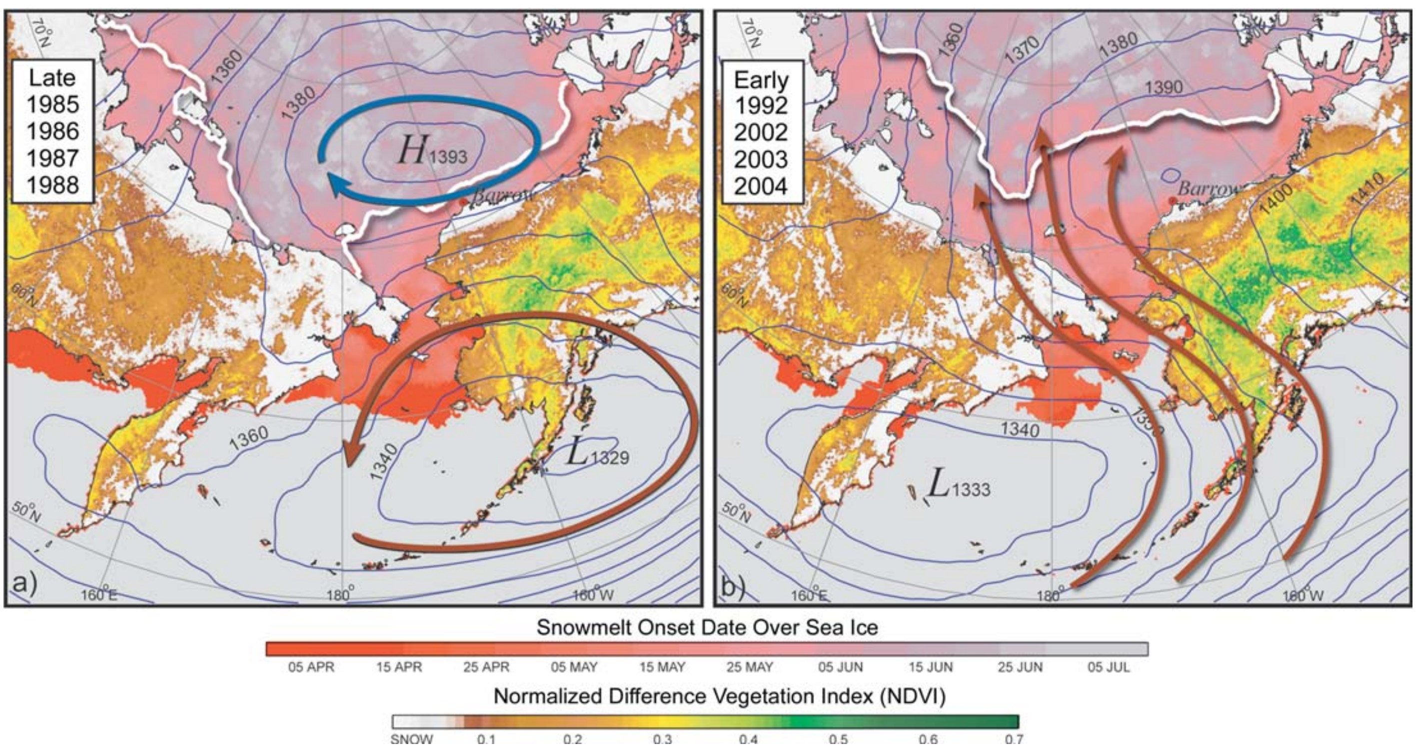
On a more regional scale, shifts in atmospheric circulation patterns also influence the annual



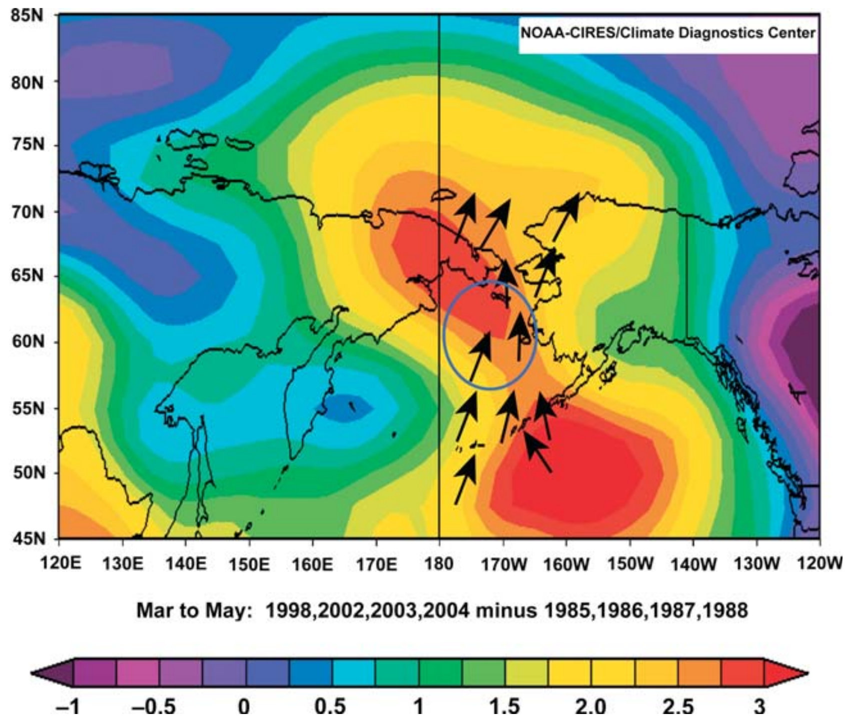
The main currents of the Arctic Ocean. During periods of high AO index, the Beaufort Gyre weakens, and divergent ice is entrained into the Transpolar Drift Stream, where it is exported from the Basin east of Greenland.

cycles of snow and sea ice. In the Pacific Arctic, variations in air temperatures and clouds correlate with the frequency and intensity of southwesterly winds. Airflow in this region varies with the juxtaposition of the Aleutian Low (AL) and the Beaufort Sea Anticyclone (BSA). It is the persistence of clockwise winds within the BSA that drives the Beaufort Gyre. An examination of these synoptic features provides insights on what may underlie the regional anomalies in snow and sea ice cover.

For years with minimum sea ice retreat, it is typical for the BSA and AL to be strongly coupled during March, April, and May, forming a dipole pattern. The BSA effectively blocks Pacific air from flowing into the Arctic. Such a pattern keeps northern regions cold and relatively dry and constrains the circulation of ice within the Beaufort Gyre. Climatologically, in late May the North Slope of Alaska and eastern Siberia remain covered in snow. Melt onset over sea ice does not commence until the first week in June north of Alaska and not until late June north of Siberia. Under these condi-



Environmental conditions over the Pacific Arctic averaged for years with minimum (left) and maximum (right) sea ice retreat. The extent of late summer ice retreat, defined as the southern limit of more than 50% mean ice concentration during late September, is shown as a bold white line. Thin blue lines depict 10-m contours of mean March–May 850-hPa geopotential heights from the NCEP/NCAR 40-year Reanalysis Project. These synoptic patterns for spring represent a critical transition period in the annual cycles of snow and sea ice. Geopotential is commonly used as a vertical coordinate when describing large-scale flow patterns, where larger values at a prescribed pressure level (e.g., 850 mb) indicate higher atmospheric pressure. Generalized circulation patterns are shown with bold vectors. Mean melt onset dates over sea ice are color-shaded for areas where ice concentrations averaged more than 50% during the second half of May. Vegetation greenness is depicted by the mean maximum NDVI (Normalized Difference Vegetation Index), also during the last two weeks in May, derived from GIMMS NDVI-d and NDVI-n16 data sets.



Mean March–May difference field of 850-mb temperatures for (1998, 2002–2004) minus (1985–1988). A jet of air transports anomalously warm air from the North Pacific into the Arctic Basin during years of early snowmelt and large ice retreat. The southerly winds within the circle are more than 3.5 m s^{-1} more intense during years of early melt onset than for years of late onset. Temperatures aloft, over a broad region, are warmer by more than 2^{o}C during years of early melt onset. The results are derived from the NCEP/NCAR 40-year Reanalysis Project.

tions the pack does not retreat very far north of the coastlines in September, leaving stretches of the Siberian coast ice bound.

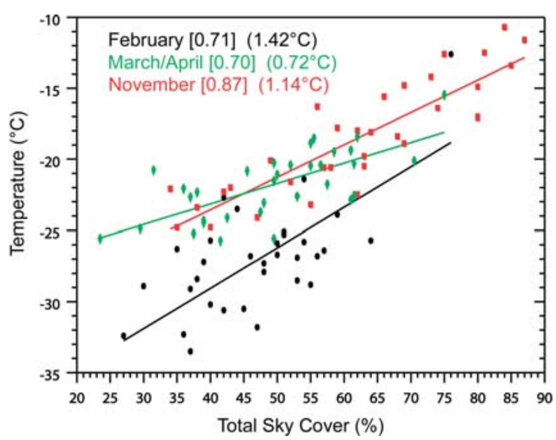
In contrast, for four recent years of extreme minimum ice extent, the spring BSA is poorly defined. Instead, a ridge of high pressure persists over eastern Alaska, and the AL is shifted westward. This pattern sets up a strong west-to-east gradient in the pressure field that favors the transport of warm, Pacific air northward. From the large, anomalously warm pool south of the Aleutian Islands, a "jet" transports warm, moist air well into the Arctic Basin. A region of intense southerly winds coincides with large pressure gradients south of the Bering Strait. This incursion of warm air accelerates snowmelt over Alaska and eastern Siberia and ice melt over adjacent ocean areas. By late May, Pacific air is further warmed as it flows over bare tundra (with a low albedo) being irradiated continuously by intense sunlight. This further contributes to an early onset of melt over sea ice. An early, and thus prolonged, melt season amplifies late-summer ice retreat, especially in the Pacific Arctic, where the ice pack has become younger and thinner.

Other Factors

The Role of Clouds

During years with minimum ice extent, the influx of moist air associated with the circulation pattern described above increase spring cloudiness. The presence of clouds have a profound impact on the surface temperatures in polar regions, where paradoxically, they warm rather than cool the surface. The warming is due to net cloud-radiative forcing whereby infrared (thermal) emissions from clouds exceed their cooling effects caused by increased solar reflectivity. Snow and ice surfaces absorb about 99% of this energy and reradiate much of it back into the atmosphere, which raises air temperature. Although the effect is greatest during winter, significant warming during March and April is associated with enhanced cloudiness. Empirically, a 5% increase in cloud cover leads to about 1.0°C of warming over the course of the season, with a range from about 0.7°C in spring to more than 1.4°C in winter. In summer, net cloud radiative forcing is slightly negative at BRW but is not statistically significant.

Prolonged effects of warm air incursions, augmented by cloud radiative forcing during early spring, are thought to modify the microphysical structure of the overlying snow. This "ripening" may precondition the snow so that melting accelerates during May and June, when solar insolation reaches its annual peak.



Empirical relationships of air temperature and total sky cover at Barrow, Alaska, averaged over 33 years, illustrating how the presence of clouds tends to warm the surface. Regressions for monthly mean values show correlations, given in brackets, and temperature sensitivity to a 5% increase in sky cover, given in parentheses.

Effects of Snowfall Variations

The depth of snow prior to the onset of melt is also important. Over land, for average conditions, if there is less snow on the ground when the melt begins, the snowpack will melt more quickly. And significant sea ice melt cannot begin until the

An August sun casting a warm glow over the northern coastline of Ellsmere Island, northeastern Canada. Rocky ridges of the United States Range rise above low-lying stratus clouds. There is a glint of sunlight from exposed areas of broken sea ice. The image illustrates the complexity of the dynamic and thermodynamic processes that modulate snow and sea ice cover in the Arctic. We face a great challenge to gain sufficient understanding of this system in order to forecast the ecological and sociological changes that will accompany rising global temperatures.

insulating surface layer of snow melts first. If less snow accumulates on sea ice in winter and conditions favor an earlier ripening of the snowpack, the snow cover will melt more rapidly, advancing the onset of ice melt.

Historically, direct observations of snowfall over sea ice have been made at Russian drift stations. Analyses of these data indicate reductions in winter snowfall up until the early 1990s, when, unfortunately, measurements were indefinitely suspended. Even over the terrestrial Arctic, snow depth observations are sparse and difficult to interpret because of wind-induced measurement biases.

Despite these limitations, an analysis of Arctic snow cover variations made in 2000 showed that the Northern Hemisphere snow cover had decreased by about 10% since the mid-1980s. At BRW, a 36% decrease in October–February snowfall from 1966 to 2000 was identified as a major factor in the trend toward earlier snowmelt. Because BRW has been shown to be regionally representative, it is likely that the western Arctic Ocean has experienced recent declines in snowfall as well, a condition that would exacerbate the early onset of summer ice melt.

The Albedo Effect Revisited

Finally, as a consequence of early melt onset and the longer duration of the melt season, a temperature–albedo feedback occurs that further accelerates ice melt. The albedo effect is very significant over land areas when surface reflectivity decreases rapidly at the time of snowmelt. Measurements indicate that a two-week advance in the date of snowmelt can lead to an increase of more than 1.0°C in air temperature. Because open water has a significantly lower albedo than tundra, it will absorb 7–12% more solar energy under equal illumination. The resultant increase in solar absorption by seawater warms the water column as well as the air above. Higher air temperatures feed back immediately to enhance melting, while higher water temperatures increase lateral and subsurface ice melt and extend the melt season by delaying the onset of autumn freeze. Ultimately, the ice pack will become thinner if the duration of melt becomes longer and the period of freeze shorter. Without winter recruitment of ice that is thick enough to survive the subsequent melt season, the MYI fraction will continue to decline.

Summary

Factors that influence the distributions of snow and sea ice are many and complex. Both dynamic and thermodynamic processes have contributed to the earlier onset of snowmelt and reductions of ice concentration in the Arctic. These mechanisms occur naturally but may be exacerbated by increasing global temperatures caused by greenhouse forcing. Significant regional and temporal variations in snow and ice cover are observed because forcing mechanisms interact through complicated pathways.

Recent trends appear to be related to shifts in planetary wave patterns, either on a hemispheric scale as in the case of the Arctic Oscillation or on more regional scales. The dramatic decrease in MYI in the Pacific Arctic dominates the trend observed for the entire basin. In the Pacific Arctic, the juxtaposition of the BSA and AL during spring affects the dynamic and thermodynamic processes that ultimately dictate the distributions of snow and ice.

In summary, factors contributing to the loss of snow and ice in the Pacific Arctic include the following:

- A breakdown of the BSA diminishes the strength of the Beaufort Gyre. Older ice is more readily entrained into the Transpolar Drift Stream and exported through the Fram Strait, reducing the overall age and thickness of the icepack and its resilience to summer melt.

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- A westward displacement of the AL, coupled with a high-pressure ridge over Alaska during spring, favors incursions of warm, moist Pacific air into the Arctic, promoting earlier and more rapid melt because of thermodynamic and radiative preconditioning of the snowpack. These involve sensible and latent heat exchanges at the surface through enhanced turbulence and net cloud-radiative heating caused by increased cloudiness.
- Earlier melt prolongs the melt season by enhancing the temperature–albedo feedback, exacerbating summer sea ice retreat and delaying the onset of freezing in autumn. Reductions in the mean sea ice thickness result as this cycle repeats.
- Under conditions of reduced snowfall, snowmelt and subsequent icemelt occur more rapidly and the albedo feedback is further prolonged, enhancing processes described above. Snowfall variations are also a function of varying modes of atmospheric circulation (now under investigation).

The question arises as to whether the recent retreat of Arctic sea ice is a manifestation of natural, low-frequency climate oscillations or an early signal of anthropogenic forcing. Are these mechanisms now self-propagating as a consequence of increasing global temperatures? Stroeve et al. (2005) questioned whether "the extreme ice minima of 2002–2004 represent the crossing of a threshold," in which case thinner ice cannot survive longer summer melt seasons. Lindsay and Zhang (2005) suggested the system may have already "tipped" into a new equilibrium state, in which summers will be characterized by vast regions of open water. The mechanisms underlying major shifts in planetary circulation and their influence on regional-scale dynamic and thermodynamic processes must be better understood to determine the likelihoods of future scenarios.

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