Arctic Report Card: *Update for 2009*

Tracking recent environmental changes

Warming of the Arctic continues to be widespread, and in some cases, dramatic. Linkages between air, land, sea, and biology are evident.

Sea Ice: Multi-year ice is going away

Melting multi-year sea ice in the Arctic Ocean.
Credit: Kitty Mecklenburg

■ (red) Atmosphere	■ (yellow) Ocean
■ (red) Sea Ice	■ (red) Greenland
■ (yellow) Biology	■ (yellow) Land

Red boxes: Consistent evidence of warming.
Yellow boxes: Many indications of warming.

Atmosphere
Large scale wind patterns impacted by loss of summer sea ice

Sea Ice
Multi-year sea ice is being replaced by first year sea ice

Ocean
Upper ocean remains warm and less salty

Land
Increased runoff in Siberia, less snow in North America

Greenland
Ice sheet loss continues

Biology
High Arctic species impacted by loss of sea ice

October 2009

Citing the complete report:
Richter-Menge, J., and J.E. Overland, Eds., 2009: Arctic Report Card 2009, http://www.arctic.noaa.gov/reportcard.

Citing an essay (example):
Perovich, D., R. Kwok, W. Meier, S. V. Nghiem, and J. Richter-Menge, 2009: Sea Ice Cover [in Arctic Report Card 2009], http://www.arctic.noaa.gov/reportcard.

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Atmosphere

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October 9, 2009

Summary

It is apparent that the heating of the ocean in areas of extreme summer sea ice loss is directly impacting surface air temperatures over the Arctic Ocean, where surface air temperature anomalies reached an unprecedented +4°C during October through December 2008. There is evidence that the effect of higher air temperatures in the lower Arctic atmosphere is contributing to changes in the atmospheric circulation in both the Arctic and northern mid-latitudes.

The annual mean Arctic temperature for the year 2008 was the fourth warmest year for land areas since 1990 (Figure A1). This continued the 21st century positive Arctic-wide surface air temperature (SAT) anomalies of greater than 1.0° C, relative to the 1961–1990 reference period. The mean annual temperature for 2008 was cooler than 2007, coinciding with cooler global and Pacific temperatures (Hansen, 2009). The outlook is for increased temperatures, because there are currently (October 2009) El Nino conditions which are expected to continue through winter 2009–2010.

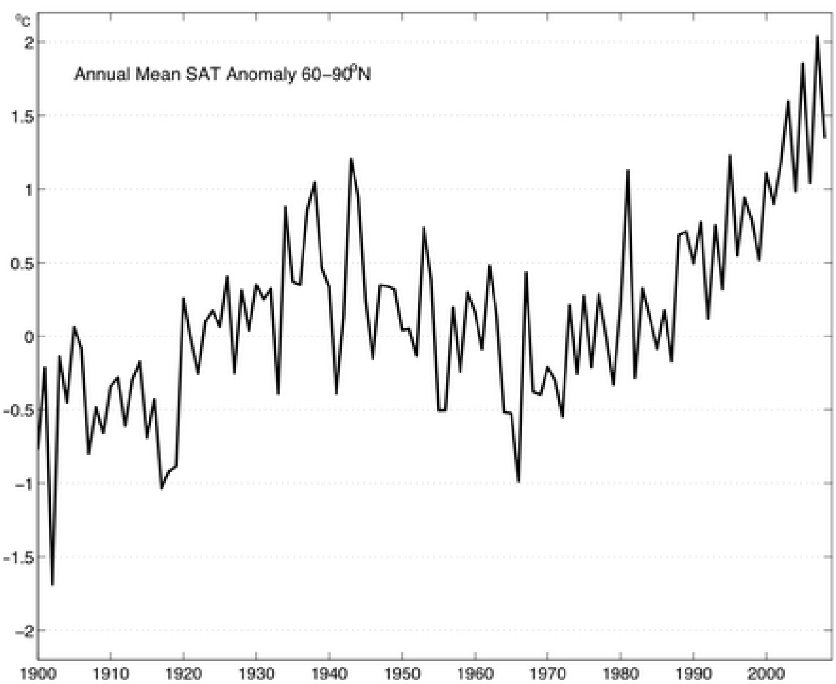

Figure A.1. Arctic-wide annual averaged surface air temperature anomalies (60°–90°N) based on land stations north of 60°N relative to the 1961–90 mean. From the CRUTEM 3v dataset, (available online at www.cru.uea.ac.uk/cru/data/temperature/ . Note this curve does not include marine observations.

During October through December 2008 SAT anomalies remained above an unprecedented +4° C across the central Arctic (Fig. A2(A)). This is linked to summer sea ice conditions. The summer of 2008 ended with nearly the same extreme minimum sea ice extent as in 2007, characterized by extensive areas of open water (see sea ice section). This condition allows extra heat to be absorbed by the ocean from longwave and solar radiation throughout the summer season, which is then released back to the atmosphere in the following autumn (Serreze et al., 2009). We expect similar warm fall temperatures over the Arctic in 2009, as in 2007 and 2008.

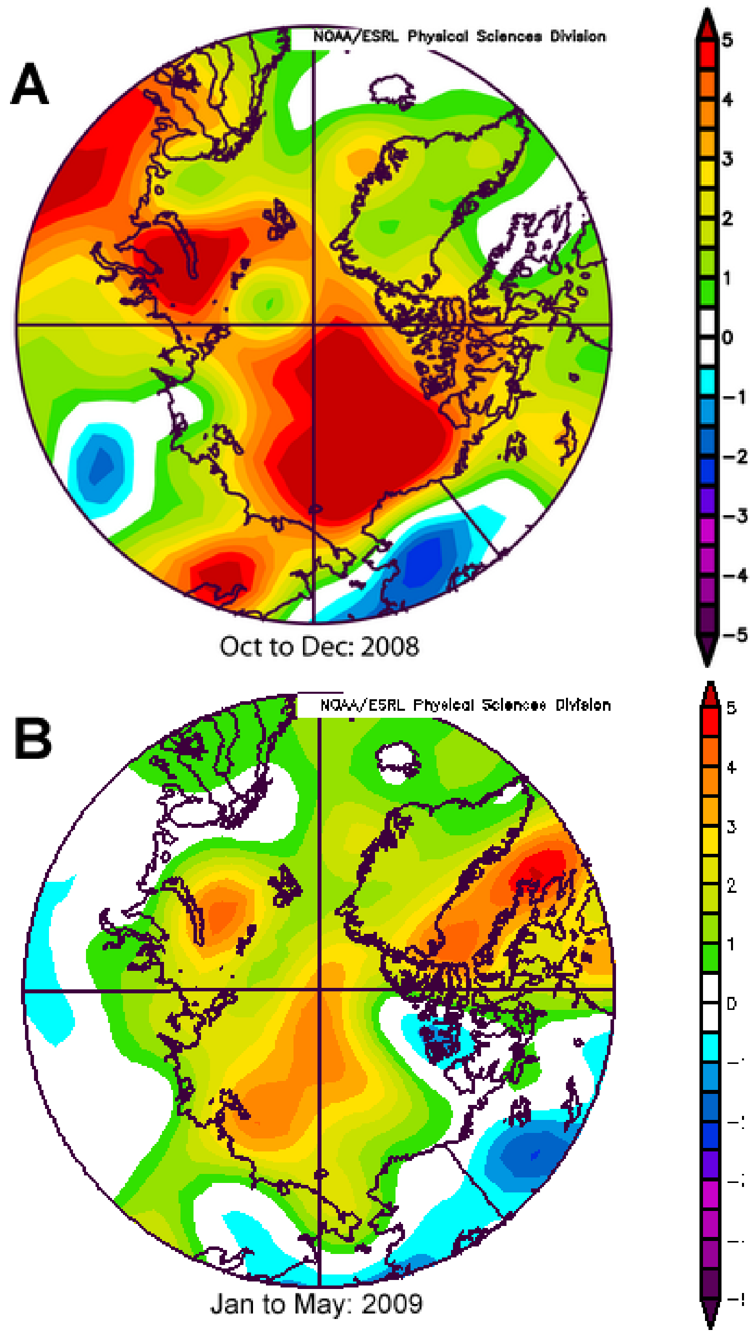

Figure A.2. Near surface air temperature anomalies for (A, top) October through December 2008 and (B, bottom) January–May 2009. Anomalies are relative to 1968–1996 mean. Data are from the NCEP – NCAR reanalysis through the NOAA /Earth Systems Research Laboratory, generated online at www.cdc.noaa.gov .

Similar to the previous years of the 21st century, in 2009 the spatial extent of positive SAT anomalies in winter and spring of greater than +1°C was nearly Arctic-wide (Figure A2 (B)), in contrast with more regional patterns in the 20th century (Chapman and Walsh, 2007). The exception was the Bering Sea/southwestern Alaska which experienced a fourth consecutive cold or average winter associated with weaker winds and colder temperatures in the North Pacific.

There is evidence that, by creating a new major surface heat source, the recent extreme loss of summer sea ice extent is having a direct feedback effect on the general atmospheric circulation into the winter season (Francis et al., 2009). Fall air temperature anomalies of greater than +1.0° C were observed well up into the atmosphere (Figure 3A), when averaged over 2003–2008 relative to a 1968–1996 base period. The higher temperatures in the lower troposphere decrease the atmospheric air density and raise the height of upper-air-constant-pressure levels over the Arctic Ocean (Figure 3B). These increased heights north of 75 °N weaken the normal north-to-south pressure gradient that drives the normal west-to-east airflow in the upper troposphere. In this sense, the effect of higher air temperatures in the lower Arctic atmosphere is contributing to changes in the atmospheric circulation in both the Arctic and northern mid-latitudes. For example, Honda et al. (2009) suggest a remote connection between loss of Arctic sea ice and colder temperatures over eastern Asia.

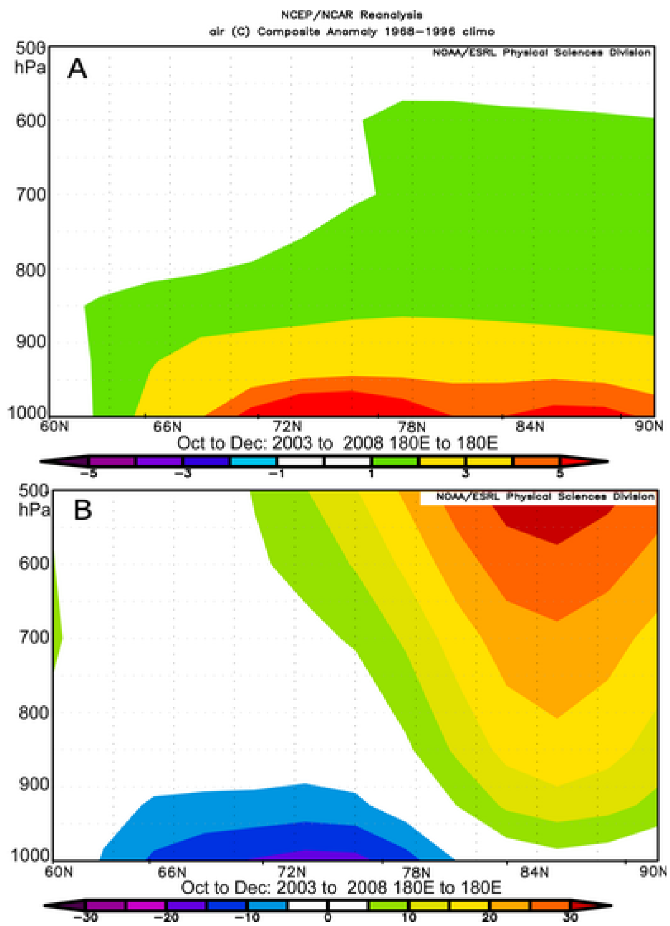

Figure A.3. Vertical cross section from 60° to 90° N along 180° longitude averaged for October–December 2003 through 2008 (years for which summertime sea ice extent fell to extremely low values) for (A) air temperature, and (B) geopotential height. Data are from the NCEP – NCAR reanalysis available online at www.cdc.noaa.gov.

The climate of the Arctic is influenced by repeating patterns of sea level pressure that can either dominate during individual months or represent the overall atmospheric circulation flow for an entire season. The main climate pattern for the Arctic is known as the Arctic Oscillation (AO) with anomalous winds that blow counter-clockwise around the pole when the pattern is in its positive phase. A second wind pattern has been more prevalent in the 21st century and is known as the Arctic Dipole (AD) pattern (Wu et al., 2006; Overland et al., 2008). The AD pattern has anomalous high pressure on the North American side of the Arctic and low SLP on the Eurasian side. This implies winds blowing more from south to north, compared to the AO, and increasing transport of heat into the central Arctic Ocean. The AD pattern occurred in all summer months of 2007 and helped support the major 2007 summer reduction in sea ice extent (Overland et al., 2008). Fall 2008 and winter/spring 2009 showed a return of the AO pattern, but also considerable month to month variability in the presence of these various climate patterns.

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Sea Ice Cover

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October 19, 2009

New! Monthly Sea Ice Outlook from SEARCH/Arcus

Summary

One of the most dramatic signals of the general Arctic-wide warming trend in recent years is the continued significant reduction in the extent of the summer sea ice cover and the decrease in the amount of relatively older, thicker ice. The extent of the 2009 summer sea ice cover was the third lowest value of the satellite record (beginning in 1979) and >25% below the 1979–2000 average.

Sea ice extent

Sea ice extent is the primary parameter for summarizing the state of the Arctic sea ice cover. Microwave satellites have routinely and accurately monitored the extent since 1979. There are two periods that define the annual cycle and thus are of particular interest: March, at the end of winter when the ice is at its maximum extent, and September, when it reaches its annual minimum. Maps of ice coverage in March 2009 and September 2009 are presented in Figure S1, with the magenta line denoting the median ice extent for the period 1979–2000.

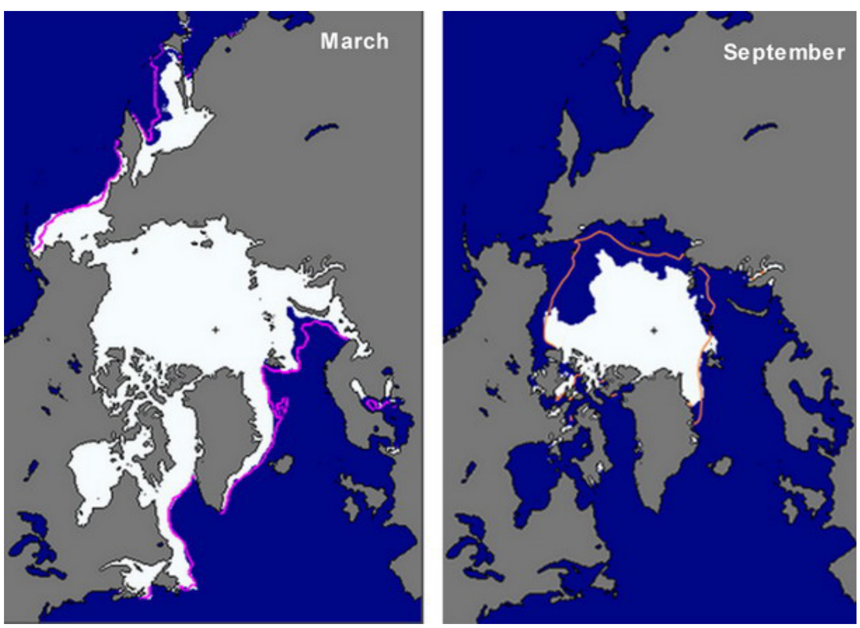

Figure S1. Sea ice extent in March 2009 (left) and September 2009 (right), illustrating the respective winter maximum and summer minimum extents. The magenta line indicates the median maximum and minimum extent of the ice cover, for the period 1979–2000. [Figures from the National Snow and Ice Data Center Sea Ice Index: nsidc.org/data/ seaice_index.]

On September 12, 2009 sea ice extent reached a 2009 minimum of 5.1 million km^2. The 2009 summer minimum is the third-lowest recorded since 1979. It was 0.6 million km^2 greater than 2008 and 1.0 million km^2 above the record low in 2007. Surface air temperatures through the 2009 summer were relatively cooler, particularly in the Chukchi and Beaufort seas. Winds in 2009 also tended to disperse the ice pack over a larger region. While the 2009 minimum was an increase over the two previous years, it was still 1.6 million km^2 below the 1979 to 2000 average minimum. The March 2009 ice extent was 15.2 million km^2, the same as in 2008 and only 4% less that the 1979–2000 average of 15.8 million km^2.

The time series of the anomalies in sea ice extent in March and September for the period 1979–2009 are plotted in Figure S2. The anomalies are computed with respect to the average from 1979 to 2000. The large interannual variability in September ice extent is evident. Both winter and summer ice extent exhibit a negative trend, with values of -2.5 % per decade for March and -8.9 % per decade for September over the period 1979–2009.

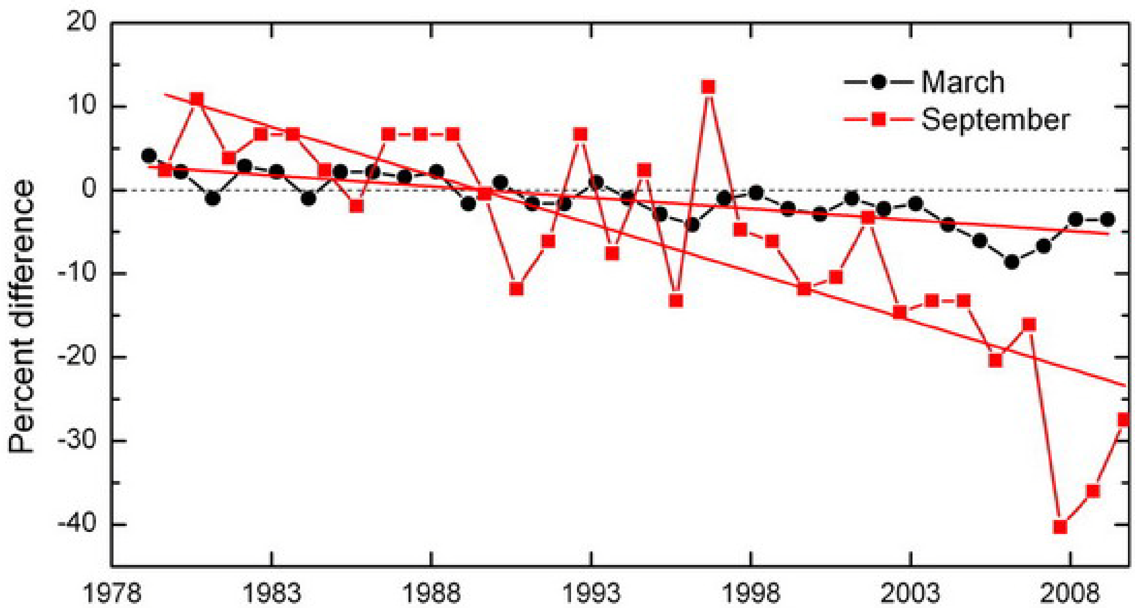

Figure S2. Time series of the percent difference in ice extent in March (the month of ice extent maximum) and September (the month of ice extent minimum) relative to the mean values for the period 1979–2000. Based on a least squares linear regression for the period 1979-2009, the rate of decrease for the March and September ice extents is –2.5% and –8.9% per decade, respectively.

Sea ice age and thickness

The age of the ice is another key descriptor of the state of the sea ice cover, since older ice tends to be thicker and more resilient than younger ice. A simple two-stage approach classifies sea ice into first year and multiyear ice. First-year is ice that has not yet survived a summer melt season, while multi-year ice has survived at least one summer and can be several years old. Satellite derived maps of ice age for March of 2007, 2008, and 2009 are presented in Figure S3.

Figure S3. Arctic sea ice distribution in March of 2007, 2008, and 2009. Multiyear ice is in white, mixed ice aqua, first-year ice teal, and ice with melting surface red. Dark blue is for open water and brown for land. From a combination of AVHRR and SSM/I satellite observations and results from drifting ice buoys. (courtesy of Son Nghiem)

In the past decade, the extent of multiyear sea ice rapidly reduced at a rate of 1.5×10^6 km^2 per decade, triple the reduction rate during the three previous decades (1970–2000). Springtime multiyear ice extent was the lowest in 2008 in the QuikSCAT data record since 2000. QuikSCAT results in March 2009 showed a multiyear ice extent of 3.0 ± 0.2 million km^2. This was 0.3 million km^2 larger than the multiyear ice extent on the same date in 2008, even though the total sea ice extent was similar in the spring of 2008 and 2009. While the multiyear ice extent was similar in March 2008 and 2009, its distribution was quite different. More specifically, in 2008 there was a significant amount of multiyear ice the Beaufort Sea and in 2009 there was a large amount of multiyear ice the central Arctic Ocean.

Recent estimates of Arctic Ocean sea ice thickness from satellite altimetry show a remarkable overall thinning of ~0.6 m in ice thickness between 2004 and 2008 (Figure. S4a). In contrast, the average thickness of the thinner first-year ice in mid-winter (~2 m), did not exhibit a downward trend. Seasonal ice is an important component covered more than two-thirds of the Arctic Ocean in 2008. The total multiyear ice volume in the winter experienced a net loss of more than 40% in the four years since 2005 while the first year ice cover gained volume due to increased overall coverage of the Arctic Ocean. The declines in total volume and average thickness (black line in Figure S4a) are explained almost entirely by thinning and loss of multiyear sea ice due to melting and ice export. These changes have resulted in seasonal ice becoming the dominant Arctic sea ice type, both in terms of area coverage and of volume.

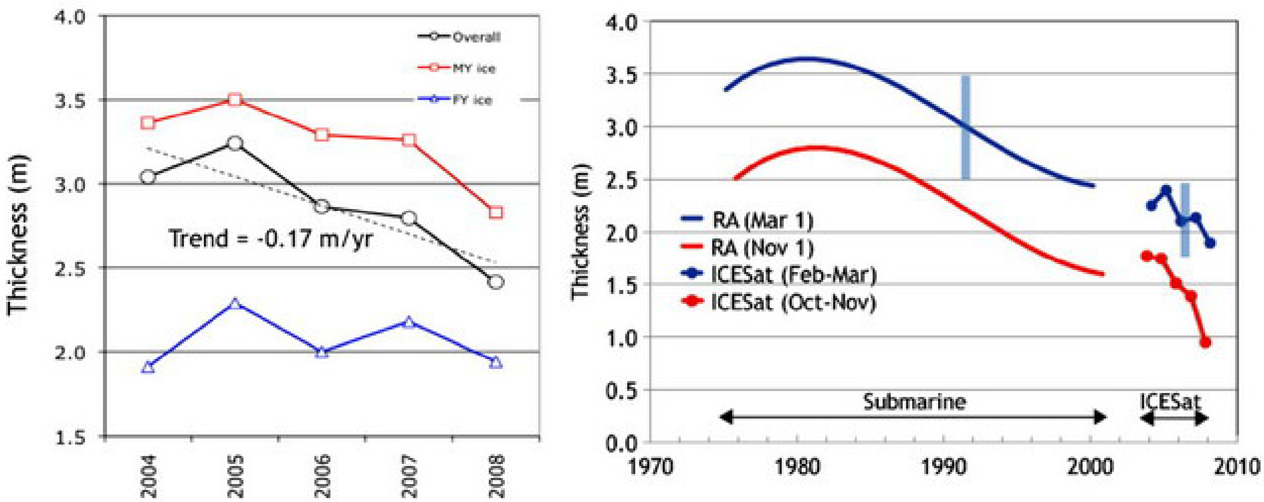

Figure S4. (a) Winter Arctic Ocean sea ice thickness from ICESat (2004–2008). The black line shows the average thickness of the ice cover while the red and blue lines show the average thickness in regions with predominantly multiyear and first-year ice, respectively. b) Interannual changes in winter and summer ice thickness from the submarine and ICESat campaigns within the data release area spanning a period of more than 30 years. The data release area covers approximately 38% of the Arctic Ocean. Blue error bars show the uncertainties in the submarine and ICESat data sets. (after Kwok et al., 2009 and Kwok and Rothrock, 2009)

The recent satellite estimates were compared with the longer historical record of declassified sonar measurements from US Navy submarines (Figure S4b). Within the submarine data release area (covering ~38% of the Arctic Ocean), the overall mean winter thickness of 3.6 m in 1980 can be compared to a 1.9 m mean during the last winter of the ICESat record—a decrease of 1.7 m in thickness. This combined submarine and satellite record shows a long-term trend of sea ice thinning over submarine and ICESat records that span three decades. The contribution of the increasing fraction of first year ice to the long term thickness trend remains to be determined.

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Ocean

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August 26, 2009

Summary

In 2008, there was an unprecedented amount of fresh water in the surface layer of the Arctic Ocean. The source of the fresh water was melting sea ice. The heating of the ocean in areas of extreme summer sea ice loss (for instance, summer surface water temperatures in the Beaufort Sea were more than 3°C above average) was contributing to record high surface air temperatures in the fall (October through December) over the Arctic Ocean.

Circulation

In 2008, the ocean surface circulation regime in the central Arctic was anticyclonic (clockwise) in winter and summer (Fig. O.1). The intensity of motion was weaker than observed in 2007, consistent with changes in the observed sea level atmospheric pressure patterns (see section 5b). In winter the major flow stream removed sea ice from the Kara and Laptev Seas, while in the summer sea ice from the Canada Basin was transported toward the Fram Strait. Data from satellites and drifting buoys (Proshutinsky et al. 2009) indicate that the entire period of 1997–2008 has been characterized by a relatively stable anticyclonic ocean surface circulation regime. This circulation pattern was the result of a higher sea level atmospheric pressure over the Arctic Ocean, relative to the 1948–2008 mean, and the prevalence of anticyclonic winds. These conditions have significantly influenced the sea ice cover, oceanic currents, and ocean freshwater and heat content.

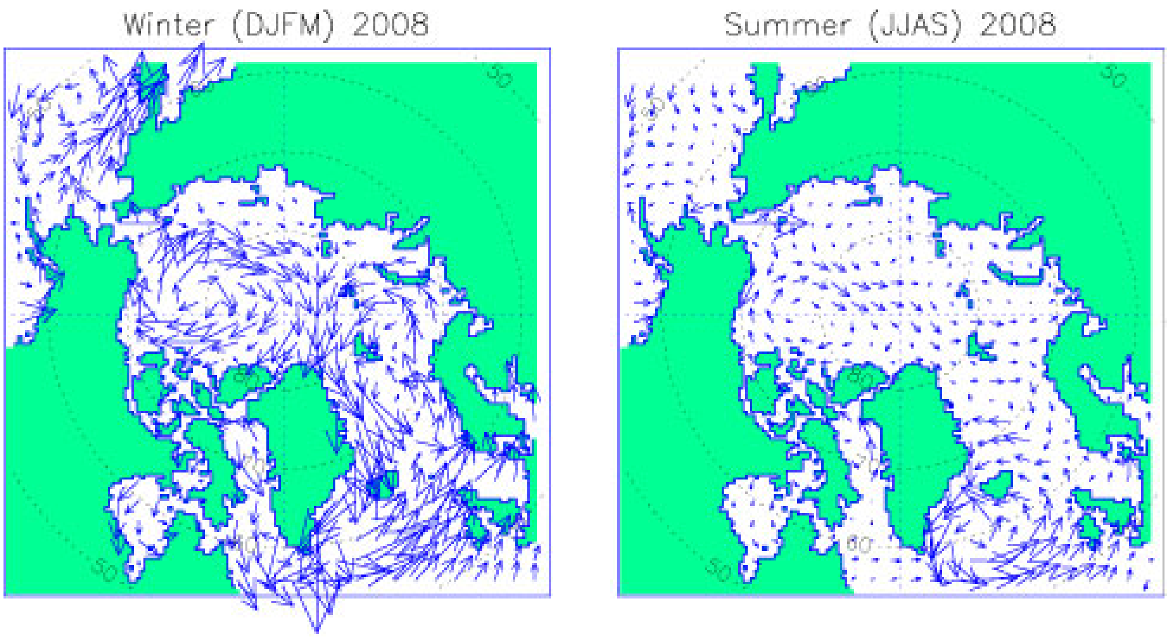

Figure O.1. Simulated circulation patterns of the upper-ocean wind-driven circulation in (left) winter and (right) summer in 2008. Both patterns are identified as anticyclonic (clockwise). The intensity of anticyclonic circulation in summer 2008 has reduced relative to 2007 (see Proshutinsky and Johnson 1997 for details).

Water temperature and salinity

Upper-ocean temperatures in summer 2008 were not quite as high as in the record-breaking summer of 2007. Although the position of the September ice edge did not change significantly in 2008 relative to 2007, the timing of ice retreat was different. Early ice retreat from the Beaufort Sea in 2008 led to anomalously high sea surface temperatures that exceeded even those in 2007 in this region (Fig. O.2). However, ice retreat in the Chukchi and east Siberian Seas occurred relatively late in the summer, leading to near-normal or only slightly above-normal ocean warming (Fig. O.2). This difference illustrates that the warming of the upper ocean is dependent not only on the position of the September ice edge but also on the time history of the ice cover over the summer. More specifically, ocean surface warming depends on the time history of atmospheric heat input to the sea surface, which depends both on atmospheric conditions (winds, clouds) and on the presence of the ice cover that acts to block this heat input (Steele et al. 2009).

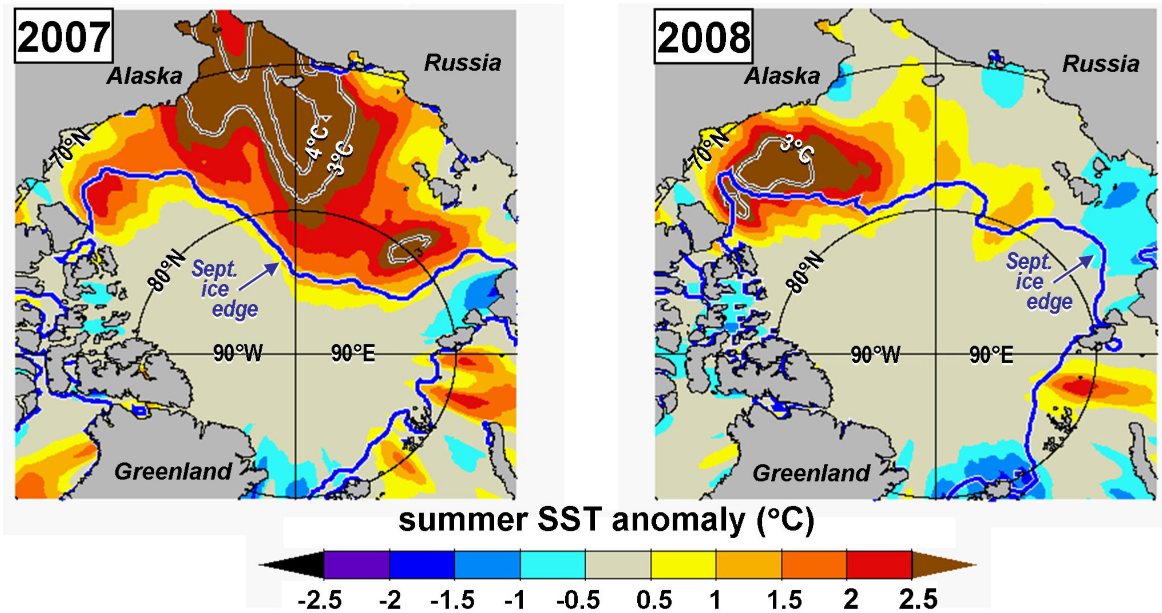

Figure O.2. Satellite-derived summer (JAS) SST anomalies (Reynolds et al. 2002) in (left) 2007 and (right) 2008, relative to the summer mean over 1982–2006. Also shown is the Sep mean ice edge (thick blue line).

Changes in the AWCT varied regionally in 2008, reflecting temporal pulses in the Atlantic water flow volume, temperature, and salinity in the Fram Strait. The Atlantic water propagates cyclonically (counterclockwise) along the Arctic Ocean continental slope, entering the Arctic Ocean via the Fram Strait west of Spitsbergen and leaving the Arctic via the Fram Strait east of Greenland. Observations at a NABOS (http://nabos.iarc.uaf.edu/) mooring in the vicinity of Spitsbergen (Fig. O.3) along the entry point of the AWCT showed that the monthly mean AWCT at 260 m reached a maximum of ~3.8°C in November–December 2006. Subsequently, the temperature at this location has declined or cooled, reaching ~2.8°C in 2008. Observations at sections crossing the continental slope in the vicinity of Severnaya Zemlya also revealed cooling of AWCT by approximately 0.5°C (Fig. O.3). This cooling signal has not reached central parts of the Arctic Ocean and the Beaufort Gyre of the Canada Basin (Proshutinsky et al. 2009). In the Beaufort Gyre region, the AWCT in 2008 was 0.80°–0.90°C, which is 0.10°C above AWCT observed in 2007 and 0.50°C above AWCT from pre-1990s climatology. In spring of 2008, data collected at the NPEO (http:// psc.apl.washington.edu/northpole/index.html) indicate that the AWCT increased to nearly 1.4°C, which is about 0.1°C higher than observed in a 2007 survey and about 0.7°C higher than pre-1990s climatology.

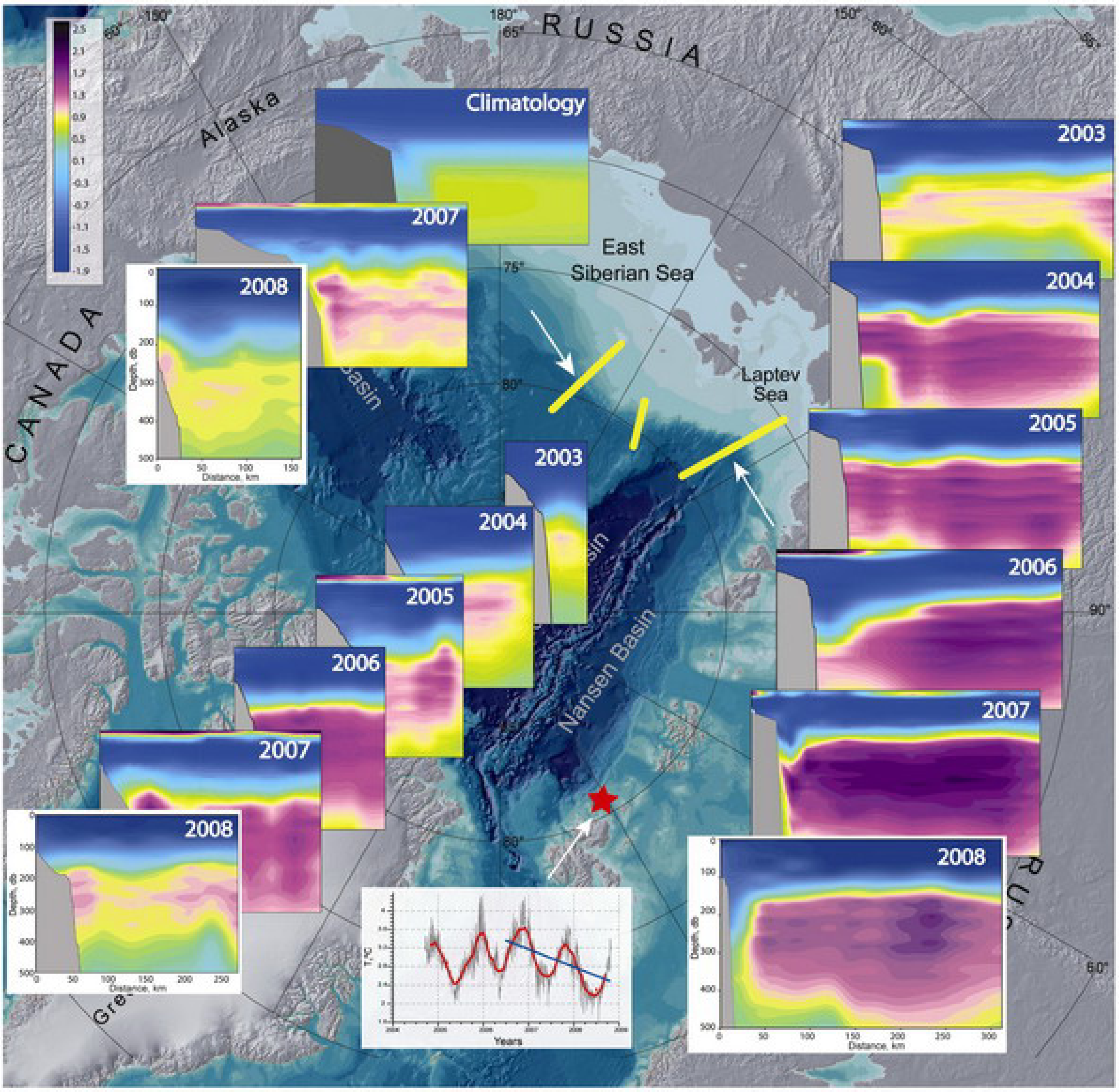

Figure O.3. Temporal (°C) and spatial variability of the AWCT. Locations of sections are depicted by yellow thick lines. Mooring location north of Spitsbergen is shown by a red star. There is a decline of Atlantic water temperature at 260 m at mooring locations with a rate of 0.5°C per year starting at the end of 2006. Some cooling in 2008 is also observed at the sections crossing the continental slope in the vicinity of Severnaya Zemlya and in the east Siberian Sea (Polyakov et al. 2009, manuscript submitted to Geophys. Res. Lett.).

Summer 2008 ship-based hydrographic surveys (Ashik, Sokolov, Frolov, and Polyakov 2008, personal communications) in different regions of the Arctic Ocean showed a continued freshening of the upper 20-m ocean layer, similar to 2007. In the 25–75-m layer, some salinification was observed in the central regions of Amundsen and Makarov Basins, while along the continental slope the water salinity remained unchanged relative to salinities observed in 2007. There was also some freshening of the deeper water layers in the Beaufort Gyre in 2008, as the surface freshening in this region was accompanied by Ekman pumping (Proshutinsky et al. 2009).

Data collected as part of the BGOS (www.whoi.edu/beaufortgyre/index.html) show that in 2000–08 the total freshwater summer content in the Beaufort Gyre has significantly increased relative to climatology of the 1970s (Arctic Climatology Project 1997, 1998; Fig. O.4). In 2008, the center of the freshwater maximum remained shifted toward Canada as in 2007 but significantly intensified relative to 2007 (Fig. O.4). As a result, the northwest part of the region is much saltier and the southeast region of the Beaufort Gyre is much fresher than in 2006–07 and, also, compared to 30 years ago. At some stations in the southeast of the Canada Basin the FWC reached the maximum observed value, increasing by as much as 11 m, which is 60% above climatology values. The freshening extends northward through the Canada and Makarov Basins to the Lomonosov Ridge (not shown). On the Eurasian side of the Lomonosov Ridge, the FWC anomaly is negative (water salinity was increased relative to climatology) with minimum FWC values of about -4 m (McPhee et al. 2009). The Beaufort Gyre heat content is significantly elevated relative to 1970s climatology (Arctic Climatology Project 1997, 1998; Fig. O.4), but no significant changes relative to 2007 heat content were registered by the BGOS in 2008.

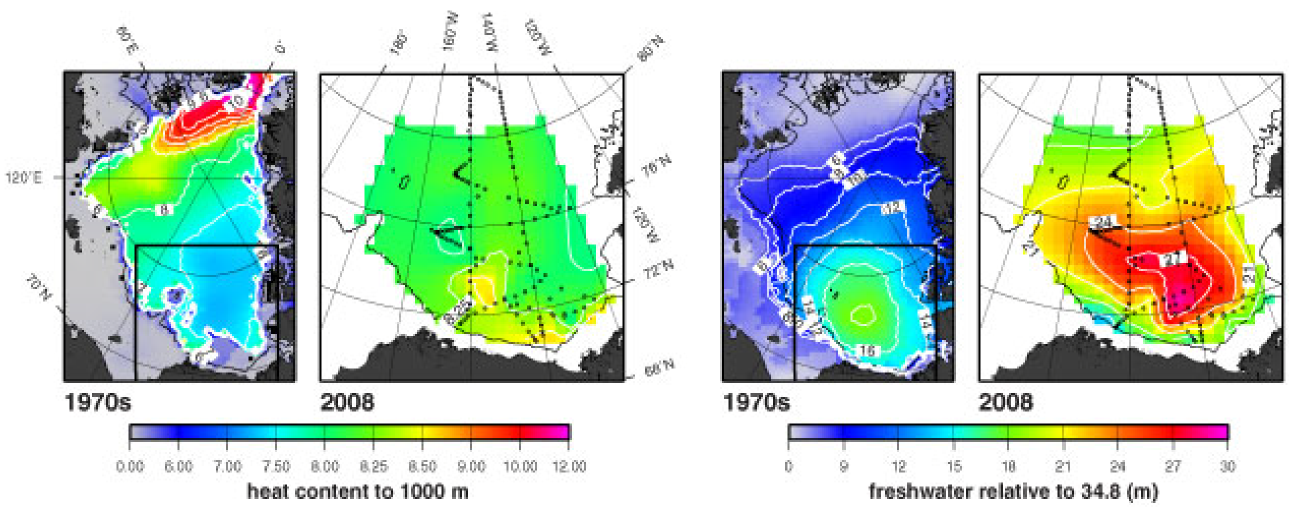

Figure O.4. (left) Summer heat (1×10^{10} J m^{-2}) and (right) freshwater (m) content. Panels 1 and 3 show heat and freshwater content in the Arctic Ocean based on 1970s climatology (Arctic Climatology Project 1997, 1998). Panels 2 and 4 show heat and freshwater content in the Beaufort Gyre in 2008 based on hydrographic survey (black dots depict locations of hydrographic stations). For reference, this region is outlined in black in panels 1 and 3. The heat content is calculated relatively to water temperature freezing point in the upper 1000-m ocean layer. The freshwater content is calculated relative to a reference salinity of 34.8.

The Bering Strait is an important gateway to the Arctic Ocean. Preliminary observations from a mooring site, established and maintained since 1990 (Woodgate et al. 2006), suggest the 2007 annual mean transport through the Bering Strait is around 1 Sv (1 Sv = 10^6 m^3 s^{-1}), greater than 2006 but comparable with previous high years, such as 2004. The same is true of the freshwater flux through the strait. The heat flux, being largely determined by the total volume flux, is also high, but in this case it appears to be somewhat higher than the 2004 values.

Sea Level

Figure O5 shows SL time series from nine coastal stations in the Siberian Seas, having representative records for the period of 1954–2008 (Arctic and Antarctic Research Institute data archives). For the nine stations, the rate for 1954–89, after the GIA, was 1.94 ± 0.47 mm yr^{-1}. This compares to an estimated rate of 1.85 ± 0.43 mm yr^{-1} along the Arctic coastlines over the same period, based on 40 arctic coastal stations (Proshutinsky et al. 2004). Addition of 1990–2008 data increases the estimated rate of SL rise for the nine stations in the Siberian seas, beginning in 1954, to 2.68 ± 0.45 mm yr^{-1} (after correction for GIA).

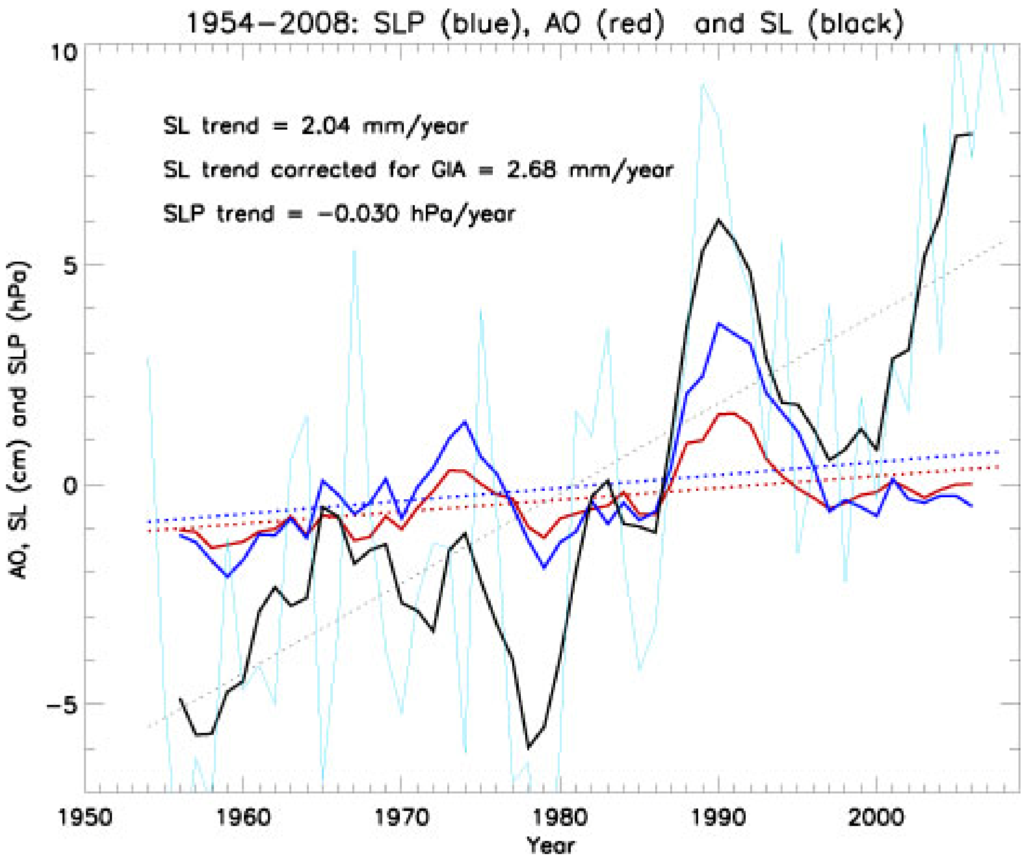

Figure O.5. The 5-yr running mean time series: annual mean sea level at nine tide gauge stations located along the Kara, Laptev, east Siberian, and Chukchi Seas' coastlines (black line). The red line is the anomalies of the annual mean AO Index multiplied by 3. The dark blue line is the sea surface atmospheric pressure at the North Pole (from NCAR–NCECEP reanalysis data) multiplied by -1. Light blue line depicts annual sea level variability.

Until 1996, SL correlates relatively well with the times series of the AO Index and sea level atmospheric pressure at the North Pole (Fig. O5). In contrast, from 1997 to 2008 the SL has generally increased, despite the more or less stable behavior of AO and SLP. Possible reasons for the rapidly rising sea level are ocean expansion, due to heating and freshening of the Arctic Ocean, and increased rates of the Greenland ice sheet melt (see Greenland essay).

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Land

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Summary

Observations of land-based changes in the Arctic cover a wide spectrum, including variations and trends in vegetation, permafrost, river discharge, snow cover, and mountain glaciers and ice caps. In general, these observations present further evidence of the impact of a general, Arctic-wide warming trend that is accompanied by high variability from year to year and region to region. For instance, the 2007/08 and 2008/09 snow cover seasons marked a continuation of the trend towards shorter snow seasons due to earlier spring melt, which has been observed during the last two decades following a rapid reduction in snow cover duration that occurred in the 1980's. Despite this overall trend, there was evidence of considerable annual and regional variability. The Arctic 2008 spring melt exhibited close to normal conditions over Eurasia, but the earliest snow cover disappearance in the period of record (1966–present) over North America. In 2008/09, the Arctic snow cover was slightly deeper than average in many areas, and the onset of snow melt was near normal or slightly later than normal across large regions of the Arctic, yet the melt intensity was sufficient to again produce an earlier than usual disappearance of snow.

Other observations reveal that there has been a general increase in land-surface temperatures and in permafrost temperatures during the last several decades throughout the Arctic region. New permafrost data from Russia show striking similarity to observations made in Alaska, with permafrost temperature typically increased by 1 to 2°C in the last 30 to 35 years. Significant losses in the mass of ice sheets and the area of ice shelves continued, with several fjords on the northern coast of Ellesmere Island being ice-free for the first time in 3000–5500 years. There continues to be a general increase of freshwater input to the Arctic Ocean from major rivers in Eurasia and North America.

Illustrating the connectivity between various elements of the Arctic system, direct observations confirm model predictions that the affects of the retreating sea ice influence the temperature and vegetation of adjacent lands. Temporal analyses generally show that, within a specific region, periods of lower sea-ice concentration are correlated with warmer land-surface temperatures and an increase in the amount of live green vegetation in the summer.

Vegetation

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There continues to be evidence of widespread changes in vegetation in northern latitudes, primarily determined from trends in terrestrial greenness as detected by the Normalized Difference Vegetation Index (NDVI) derived from the NOAA AVHRR satellites (Myneni et al. 1997; Zhou et al. 2001; Lucht et al. 2002; Jia et al. 2003; Goetz et al. 2005; Bunn et al. 2007). Changes in land cover, vegetation density, and other factors are reflected in NDVI. Overall, increasing NDVI is consistent with warming soil and air temperatures, earlier snow melt, and the expansion of shrubs and tree line to the north.

In coastal regions, models have predicted that the retreating sea ice should affect the temperature and ecosystems of adjacent lands (e.g., Lawrence et al., 2008). Time series of sea-ice area, land temperatures, and an index of photosynthetic activity (the annual maximum NDVI or MaxNDVI) were investigated for trends and variability during the period 1982–2008 along the coastlines of 14 Arctic seas. Temporal analyses of these regional time series (not shown) consistently indicate that higher land-surface temperatures and higher NDVI values correspond to below-average sea-ice concentration (Bhatt et al., 2008, 2009).

The trend analysis shows that summer sea ice within 50 km of the coast declined in all regions, with a decrease of 25% for the northern hemisphere as a whole (Fig. 1, blue bars). The largest declines were along the northern Beringia region, including the E. Siberia (-47%), W. Chukchi (-46%), and E. Chukchi (-44%) seas. This portion of the Arctic saw large areas of summer ice retreat in 2005, 2007, and 2008.

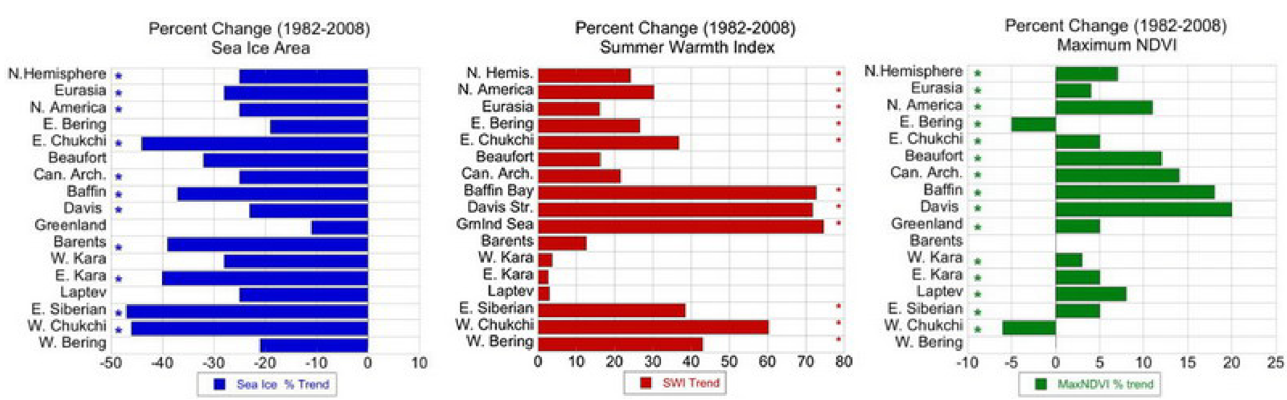

Figure 1. Blue bars: Percentage change in sea-ice area in late spring (when the long-term mean 50% concentration is reached) during 1982–2008 along the 50-km-seaward coastal margin in each of the major seas of the Arctic using 25-km resolution SSMI passive microwave Bootstrap sea-ice concentration data (Comiso and Nishio, 2008). Red bars: Percentage change in the summer land-

surface temperature landward of each sea for the entire tundra domain as measured by the summer warmth index (SWI = sum of the monthly mean temperatures above freezing, °C mo) based on AVHRR surface-temperature data (Comiso, 2003). Green bars: Percentage change in greenness for the full tundra area in the vicinity of each Arctic sea as measured by the annual maximum Normalized Difference Vegetation Index (MaxNDVI) based on revised biweekly GIMMS NDVI (Tucker et al., 2001). Asterisks denote significant trends at $p < 0.05$.

Summer tundra land temperatures as measured by the summer warmth index (sum of the monthly mean temperatures that are above freezing) increased 24% for the northern hemisphere as a whole (Fig. 1, red bars). The North America Arctic tundra experienced a 30% increase in summer land temperatures while Eurasia experienced a 16% increase. Large increases in summer warmth occurred in the vicinity of the W. Chukchi (60%) and W. Bering (43%) seas and near Davis Strait (72%), Greenland Sea (75%) and Baffin Bay (73%). Weak warming occurred along the northern coast of Russia (Laptev Sea, E. Kara Sea and W. Kara Sea).

Photosynthetic activity was determined using the MaxNDVI derived from Global Inventory Modeling and Mapping Studies (GIMMS) data set. The NDVI is an index of the photosynthetic activity that is derived from earth's reflectance in the visible and near infrared portions of the spectrum. MaxNDVI over the tundra region increased 7% for the Arctic as a whole (Fig. 1, green bars), but was variable. Larger percentage increases occurred in North America (11%) than in Eurasia (4%). The largest percentage increases were in the North American High Arctic in the vicinity of Davis Strait (20%), Baffin Bay (18%), and the Canadian Archipelago (14%) and in the Beaufort Sea (12%). Declines or no trend occurred in the Bering-Chukchi region (W. Chukchi -6%, E. Bering -5% and W. Bering 0%). The NDVI changes observed in coastal regions are in general agreement with strong increases in NDVI noted previously in the North American Arctic (Jia et al., 2003; Goetz et al., 2005; Verbyla, 2008; Raynolds et al., 2008) and with ground observations from the same regions (Tape et al., 2006; Walker et al., 2008; Epstein et al., 2008), but the new information from the High Arctic of Canada and Greenland points to previously overlooked major changes to plant productivity occurring in this region. Because of the currently low productivity in these coldest areas of the Arctic, small increases in photosynthetic activity are likely to lead to major changes in biodiversity and total plant biomass.

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Permafrost

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Observations show a general increase in permafrost temperatures during the last several decades in Alaska (Romanovsky et al., 2002; Romanovsky et al., 2007; Osterkamp, 2008), northwest Canada (Couture et al., 2003; Smith et al., 2005), Siberia (Oberman and Mazhitova, 2001; Oberman, 2008; Drozdov et al., 2008; Romanovsky et al., 2008), and Northern Europe (Isaksen et al., 2000; Harris and Haeberli, 2003). Most of the permafrost observatories in Alaska show a substantial warming during the last 20 years. The detailed characteristic of the warming varies between locations, but is typically from 0.5 to 2°C at the depth of zero seasonal temperature variations in permafrost (Osterkamp, 2008). It is worth noting that permafrost temperature has been relatively stable on the North Slope of Alaska during 2000–2008.

Permafrost temperature has increased by 1 to 2°C in northern Russia during the last 30 to 35 years (Figure P1). This observed increase is very similar in magnitude and timing to what has been observed in Alaska. Also, a common feature for Alaskan and Russian sites is more significant warming in relatively cold permafrost than in warm permafrost. This fact may be explained by a partial melting of constituent ice within a substantial portion of warm permafrost (upper 20–25 meters) with temperatures in this portion still below 0°C. This partial ice melting slows down the rate of permafrost warming as the temperature of permafrost approaches 0°C (Romanovsky, 2007). An especially noticeable permafrost temperature increase in the Russian Arctic was observed during the last two years. The mean annual permafrost temperature at 15-m depth increased by more than 0.3°C in the Tiksi area and by 0.25°C at 10-m depth in the European North of Russia.

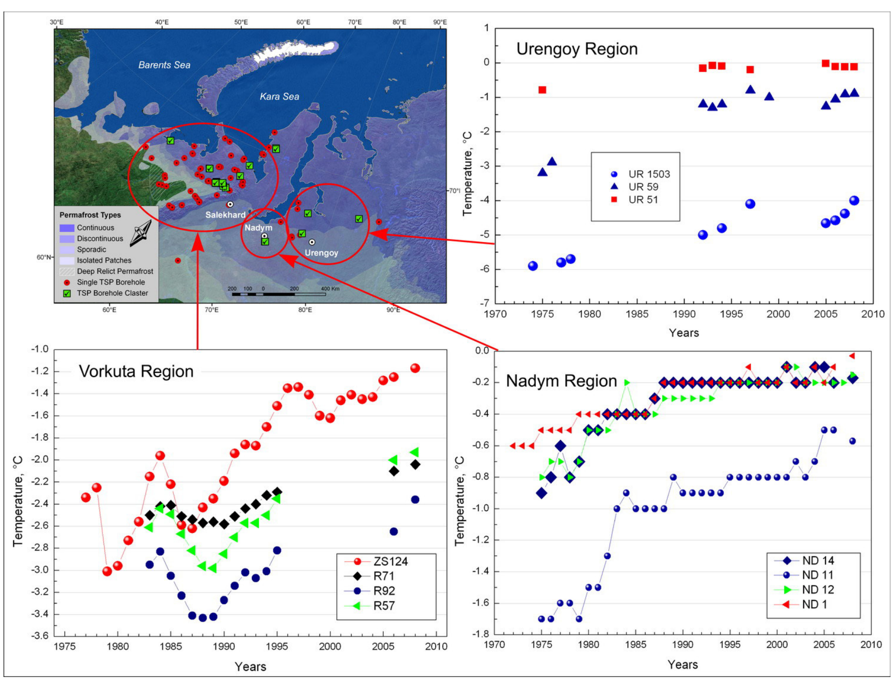

Figure P1. Left above: Location of the long-term MIREKO and the Earth Cryosphere Institute permafrost observatories in northern Russia. Left below: Changes in permafrost temperatures at 15-m depth during the last 20 to 25 years at selected stations in the Vorkuta region (updated from Oberman, 2008). Right: Changes in permafrost temperatures at 10-m depth during the last 35 years at selected stations in the Urengoy (above) and Nadym (below) regions (updated from Romanovsky et al., 2008).

The last 30-years warming in permafrost temperatures have resulted in thawing of permafrost in areas of discontinuous permafrost in Russia. Most of observed long-term thawing has occurred in the Vorkuta and Nadym research areas (Oberman, 2008). At one of the locations, the upper boundary of permafrost lowered to 8.6 m in 30 years. It lowered even more, to almost 16 m, in an area where a newly developed talik (a volume or layer of all-year-round unfrozen soil above or within the permafrost) coalesced with an already-existing lateral talik. The average increase in depth of the permafrost table in the Vorkuta and Nadym regions in Russia ranged from 0.6 to 6.7 m depending on the geographical location, ice content, lithological characteristics of sediments, hydrological, hydrogeological, and other factors.

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River Discharge

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August 27, 2009

A general increase of river discharge to the Arctic Ocean from Eurasia was observed over the period 1936–2007, with a rate of annual change (defined from the linear trend) of 2.7 ± 0.5 km^3/year (Fig. R1). The most pronounced positive (increasing) trend for the six largest Eurasian rivers is observed during the last 21 years (1987–2007), at a rate of 11.8 km^3/year. The rate of discharge has continued to increase in the 21st century. The mean 2000–2007 discharge was 171 km^3 higher (10%) than the long-term average over the period 1936–1999. A new historical maximum for Eurasian river discharge to the Arctic Ocean was observed in 2007, reaching 2250 km^3/year or 30% higher than the long-term mean discharge from 1936–1999, reported in Peterson et al. (2002).

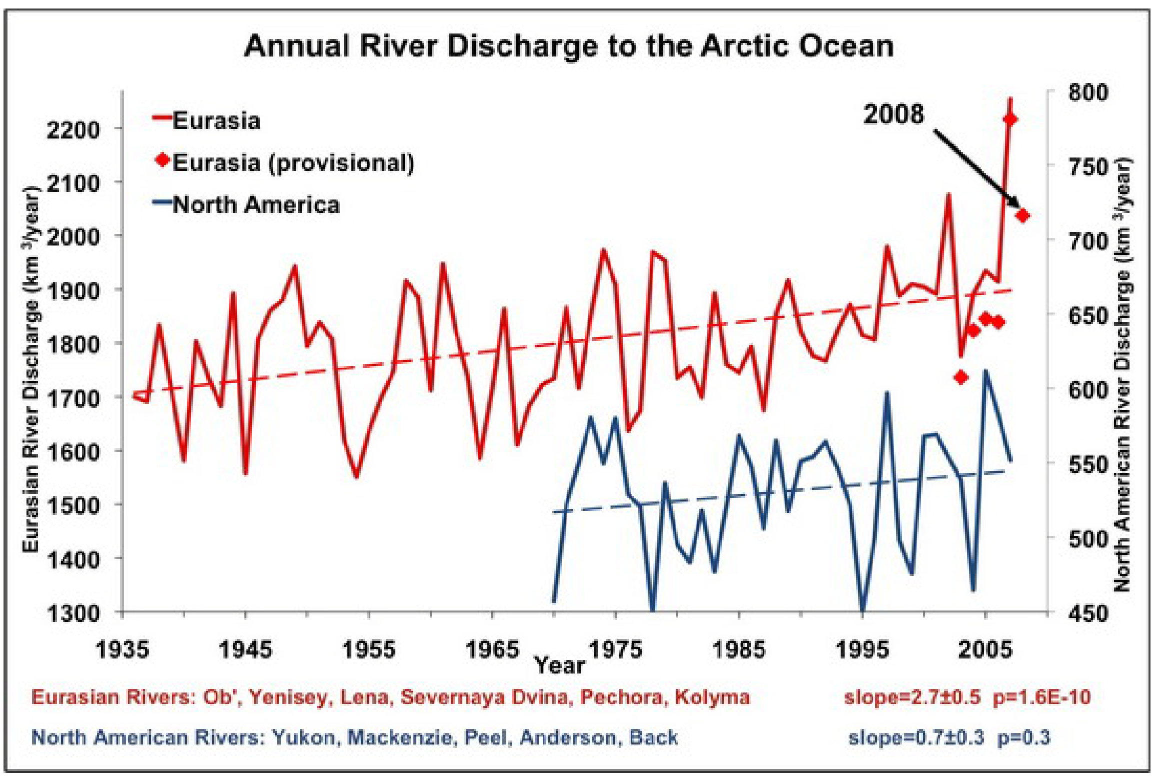

Figure R1. Total annual river discharge to the Arctic Ocean from the six largest rivers in the Eurasian Arctic for the observational period 1936–2007 (updated from Peterson et al., 2002) (red line) and from the five large North American pan-Arctic rivers over 1973–2006 (blue line). The least squares linear trend lines are shown as dashed lines. Provisional estimates of annual discharge for the six major Eurasian Arctic rivers based on near real time data from http://RIMS.unh.edu are shown as red diamonds.

The mean annual discharge to the ocean over 2000–2007 from the 5 large North American Arctic rivers based on data from the Environment Canada and USGS was about 6% (31 km^3) greater than the long-term mean from 1973–1999. The river discharge during 2007 was higher than the long-term mean and, taking into account that this year had extremely high fresh water discharge from Greenland (Mernild et al., 2009), we can estimate that 2007 showed record high total freshwater input to the Arctic Ocean from the terrestrial land surface.

Official river discharge data are usually processed and published with some delay, the longest delay often being associated with rivers in cold regions that are ice covered for extended periods (Shiklomanov et al. 2006). To provide for more timely detection and diagnosis of changing conditions, a method to estimate near-real time river discharge from the most important Russian monitoring sites, based on provisional stage measurements and river ice data, has been developed in cooperation with the Arctic and Antarctic Research Institute (AARI) (http://RIMS.unh.edu). The provisional estimates over 2003–2007 show a tendency to underestimate the annual observed values within an error of 5% of the officially released data (Figure R1). The preliminary estimate of annual river discharge to the Arctic Ocean from the major Russian rivers in 2008 was significantly greater than the long-term mean but lower than the historical maximum observed in 2007. The North American annual river discharge to the Arctic Ocean in 2008 was probably close to or slightly higher than the long-term mean. However, this estimate is much less reliable due to gaps in near real time discharge data for major North American rivers.

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Terrestrial Snow

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October 7, 2009

Overview

Northern hemisphere terrestrial snow cover exhibits a high degree of intra- and inter-seasonal variability in spatial extent, covering up to 47 million km^2 in winter, and receding to as low as 4 million km^2 in summer. Across the Arctic and sub-Arctic, snow cover is a defining characteristic of the environment, covering the landscape for up to 9 months of the year. Unlike liquid precipitation, snowfall is stored on the land surface, redistributed by wind, and metamorphosed by various physical processes before the spring melt period. For a comprehensive perspective on terrestrial snow it is necessary to consider snow cover extent (SCE: the area covered by snow), snow cover duration (SCD: how long snow is on the ground), snow water equivalent (SWE: the amount of liquid water stored in the form of snow), and snow melt timing/duration (when and for how long the snow melts).

Various satellite and ground-based measurements are available to characterize these parameters across the northern hemisphere, and assess the 2007/08 and 2008/09 snow seasons relative to the historical record. Seasonal SCD departures (difference from the 1988–2007average) were computed from the NOAA snow extent data record maintained at Rutgers University (http://climate.rutgers.edu/snowcover/). SWE is more difficult to monitor than SCD due to high spatial variability, a sparse surface observation network across the Arctic, and uncertainties in satellite datasets. The Canadian Meteorological Centre (CMC) has produced a daily global snow depth analysis (~35 km resolution) since 1998 by combining the available ground observations with a snow model (Brasnett, 1999). The main snow melt onset date across the pan-Arctic land mass was derived from satellite scatterometer measurements via QuikSCAT, using the algorithm of Wang et al. (2008).

2007/08

The 2007/08 snow season was characterized by a shorter than average snow cover season over the central Canadian Arctic, most of Europe, and eastern Siberia, with a longer than average snow season in central China and the mid-latitudes of North America (Figure S1a). Time series of fall and spring SCD anomalies (departures divided by the standard deviation over the 1988–2007 period to give an indication of relative magnitude) across the North American and Eurasian sectors of the Arctic (north of 60N) are illustrated in Figure S1b. In fall, the 2007/08 snow cover season was close to the 1988–2007 average in both regions while in spring, the North American Arctic had the earliest disappearance of snow since the start of the NOAA record which dates to 1966.

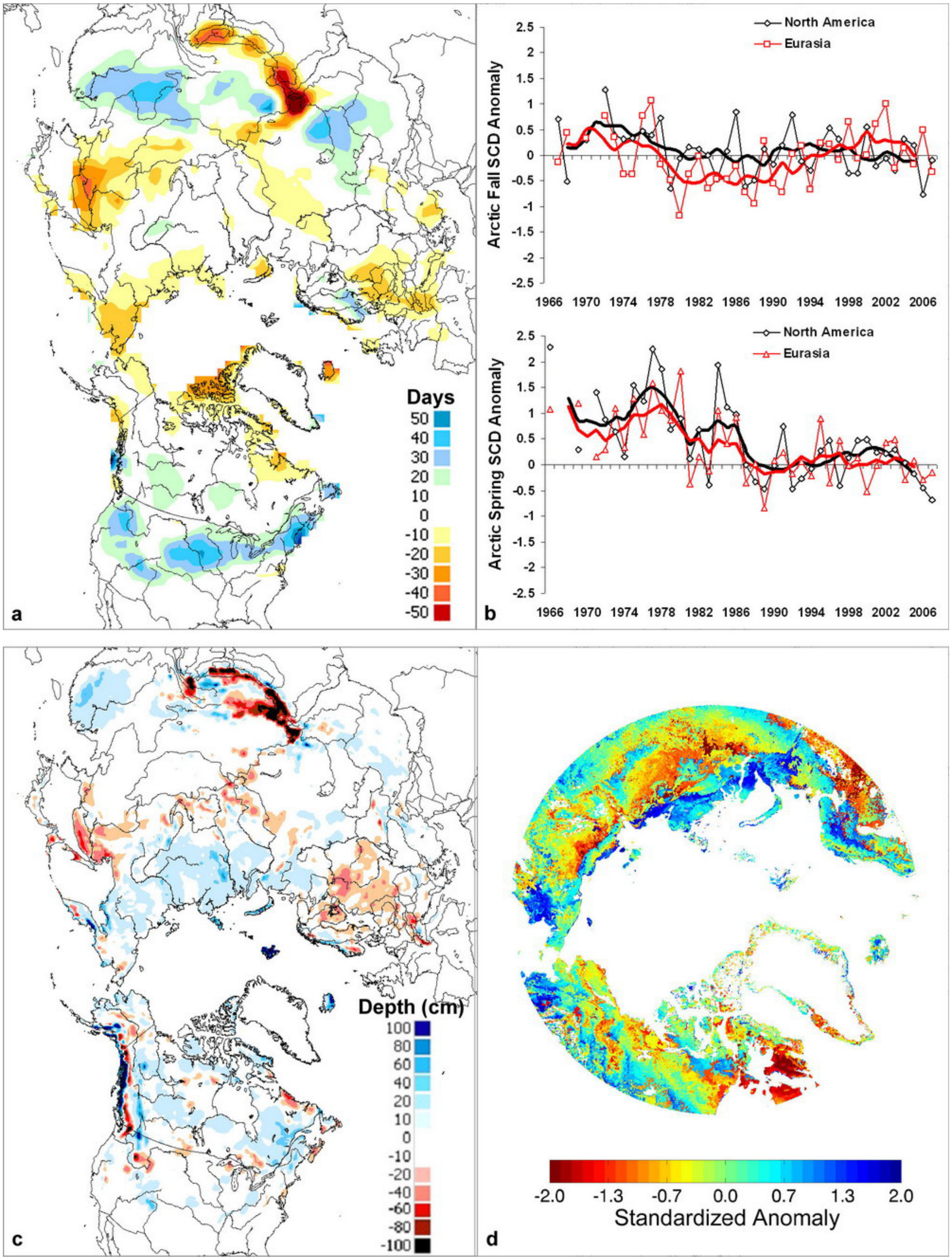

Figure S1. (a) Snow cover duration (SCD) departures (with respect to 1988–2007) for the 2007/08 snow year and (b) Arctic seasonal SCD anomaly time series (with respect to 1988–2007) from the NOAA record for the first (fall) and second (spring) halves of the snow season. Solid lines denote 5-yr moving average. (c) Maximum seasonal snow depth anomaly for 2007/08 (with respect to 1998/99–2007/08) from the CMC snow depth analysis. (d) Terrestrial snow melt onset anomalies (with respect to 2000–2008) from QuikSCAT data derived using the algorithm of Wang et al. (2008).

Maximum seasonal snow depth anomalies for 2007/08 determined from the CMC analysis are shown in Figure S1c. Below-average snow accumulation occurred across the Himalayas, Europe and northern China; above-average snow depth occurred across central North America and Siberia.

The main snow melt onset date for 2008, relative to the 9-year QuikSCAT record (2000 to 2008), confirms regional early melt onset over the North American Arctic that matches the unusually early dates of snow disappearance identified in the NOAA record (Figure S1d).

2008/09

As for the 2008/09 snow season, there was a shorter than normal snow cover season across a large portion of eastern Siberia, with strong negative anomalies in the North American sector confined to the Canadian Arctic Islands (Figure S2a). When separated for fall and spring, and averaged regionally, negative SCD anomalies were evident across Eurasia in the fall, and the entire Arctic in spring (Figure S2b). The 2009 spring Arctic snow season can therefore be characterized as shorter than normal due primarily to an early disappearance of snow cover in spring.

The shorter than average snow season in 2008/09 occurred in spite of slightly deeper than average snow depth in many parts of the Arctic (Figure S2c). Snow melt onset anomalies from QuikSCAT observations show that the initial timing of snow melt was near normal, or slightly later than normal across large regions of western Siberia, northern Europe, and the Canadian tundra (Figure S2d). Collectively, these datasets suggest that although melt was initiated near the average time, it was of sufficient intensity to rapidly remove the snowpack across large regions of the Arctic.

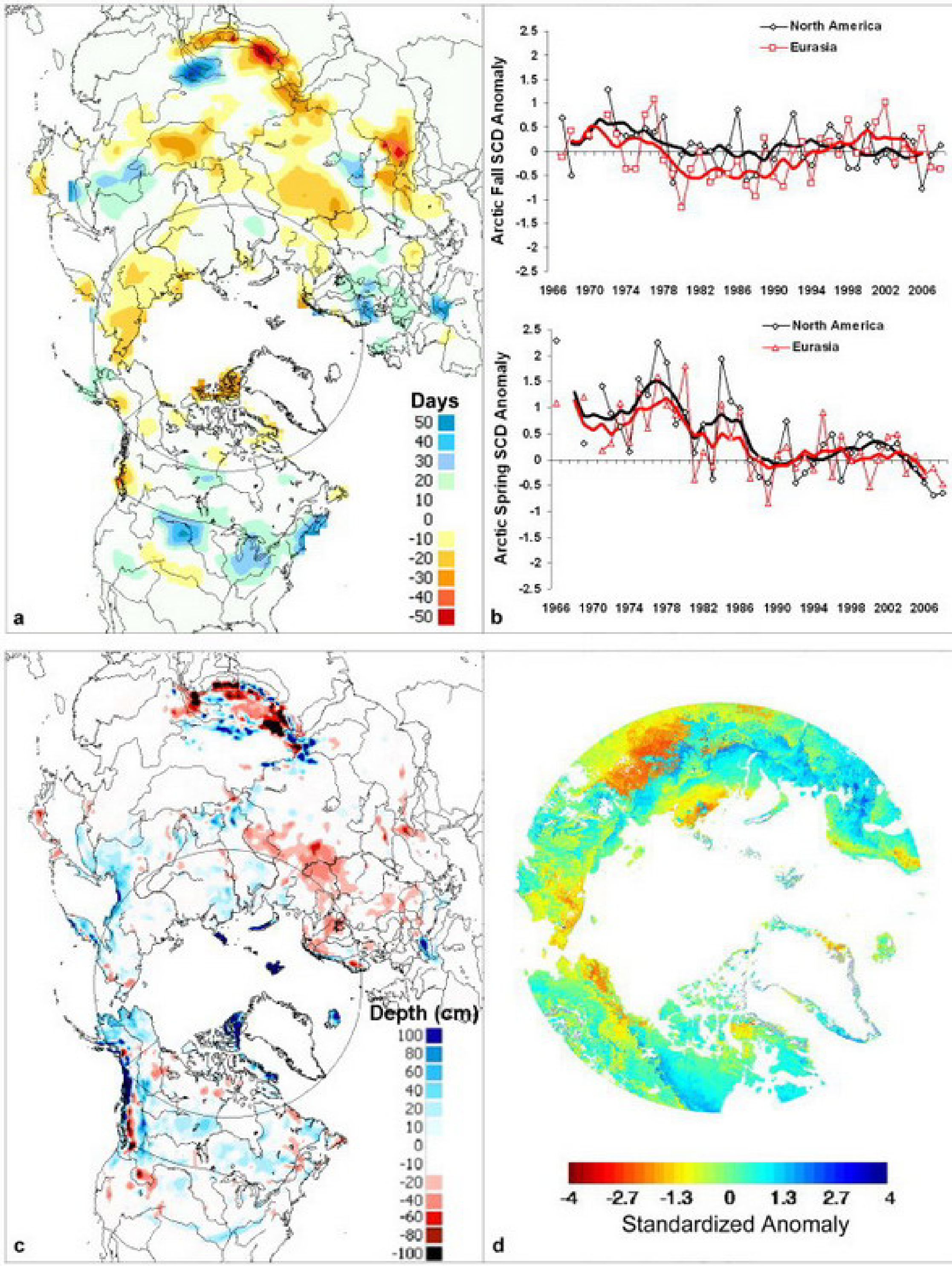

Figure S2. (a) Snow cover duration (SCD) departures (with respect to 1988–2007) for the 2008/09 snow year and (b) Arctic seasonal SCD anomaly time series (with respect to 1988–2007) from the NOAA record for the first (fall) and second (spring) halves of the snow season. Solid lines denote 5-yr moving average. (c) Maximum seasonal snow depth anomaly for 2008/09 (with respect to 1998/99–2007/08) from the CMC snow depth analysis. (d) Terrestrial snow melt onset anomalies (with respect to 2000–2009) from QuikSCAT data derived using the algorithm of Wang et al. (2008).

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Glaciers outside Greenland

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August 26, 2009

Glacier shrinkage is a major contributor to global sea level change, and mountain glaciers and ice caps may account for up to 60% of the total glacier contribution to sea level rise since the 1990's (Meier et al., 2007; Cazenave et al., 2009). Since the Arctic (including Alaska) contains nearly 50% of the total global mountain glacier and ice cap area, it has accounted for a large fraction of this contribution (50–60% in the 1961–2004 period) (Kaser et al., 2006).

Surface mass balance (annual net balance and its summer/winter components) measures how climate affects the health of Arctic glaciers. Measurements of this quantity on Arctic glaciers and ice caps suggest accelerating rates of mass loss since the early 1990's (Kaser et al., 2006). As most 2007–8 measurements are not yet available, we report results for the 2006–2007 balance year (Svalbard: 4 glaciers, Iceland: 6, Alaska:3, Arctic Canada:4). Annual surface balances were negative for 14 glaciers, positive for 2 (1 each in Iceland and Alaska) and zero for one (in Svalbard) (WGMS, 2009). The 2006–2007 annual surface balances were among the five most negative balances in the > 40-year long records from the four Canadian Arctic sites. These results suggest a continuation of the longer term trend of overall mass loss.

Summer (JJA 2008) 700 hPa air temperature and winter (September 2007–May 2008) precipitation data from the NCEP/NCAR Reanalysis serve as climatic indices for regions centered over each of the Arctic's major glaciated regions (excluding Greenland). Correlations between the 1948–2008 NCEP summer temperature series from 16 discrete regions form 4 groups (Alaska, Arctic Canada, Iceland, and the Eurasian Arctic). Measurements from glaciers in these regions suggest that inter-annual variability in the annual net balance arises primarily from variability in the summer balance (Arctic Canada), the winter balance (southern Alaska, Iceland) or both (Eurasian Arctic, with greater influence from the summer balance). The climatic indices therefore suggest that the annual mass balance was likely extremely negative in Arctic Canada, due to unusually warm summer air temperatures, and positive in Alaska due to strong positive winter precipitation anomalies (confirmed by GRACE satellite gravimetry; pers. comm. from S. Luthcke, 2009). Annual balance was likely near zero or slightly positive in the Eurasian Arctic (relatively cool summers and generally high winter precipitation) and negative in Iceland (warmer than average summer temperatures and below average winter precipitation).

Melt onset and freeze-up dates and 2008 melt season duration were determined from temporal backscatter variations measured by QuikScat's SeaWinds scatterometer (Table G1; Figure G1). In Arctic Canada, melt duration anomalies (relative to 2000–2004 climatology) on the N Ellesmere, Agassiz, and Axel Heiberg ice caps ranged from +17.6 to +22.5 days, largely due to late freeze-up (Table 1). Here, summer 2008 was the longest melt season in the 2000–2008 record. Melt duration anomalies were also strongly positive on northern Prince of Wales Icefield and Severnaya Zemlya, and positive in the southern Queen Elizabeth Islands and Baffin Island (Arctic Canada), Franz Josef Land, and Iceland. The melt season in southwest Alaska was the shortest in the nine-year record, with strongly negative melt duration anomalies, mostly due to early freeze-up.

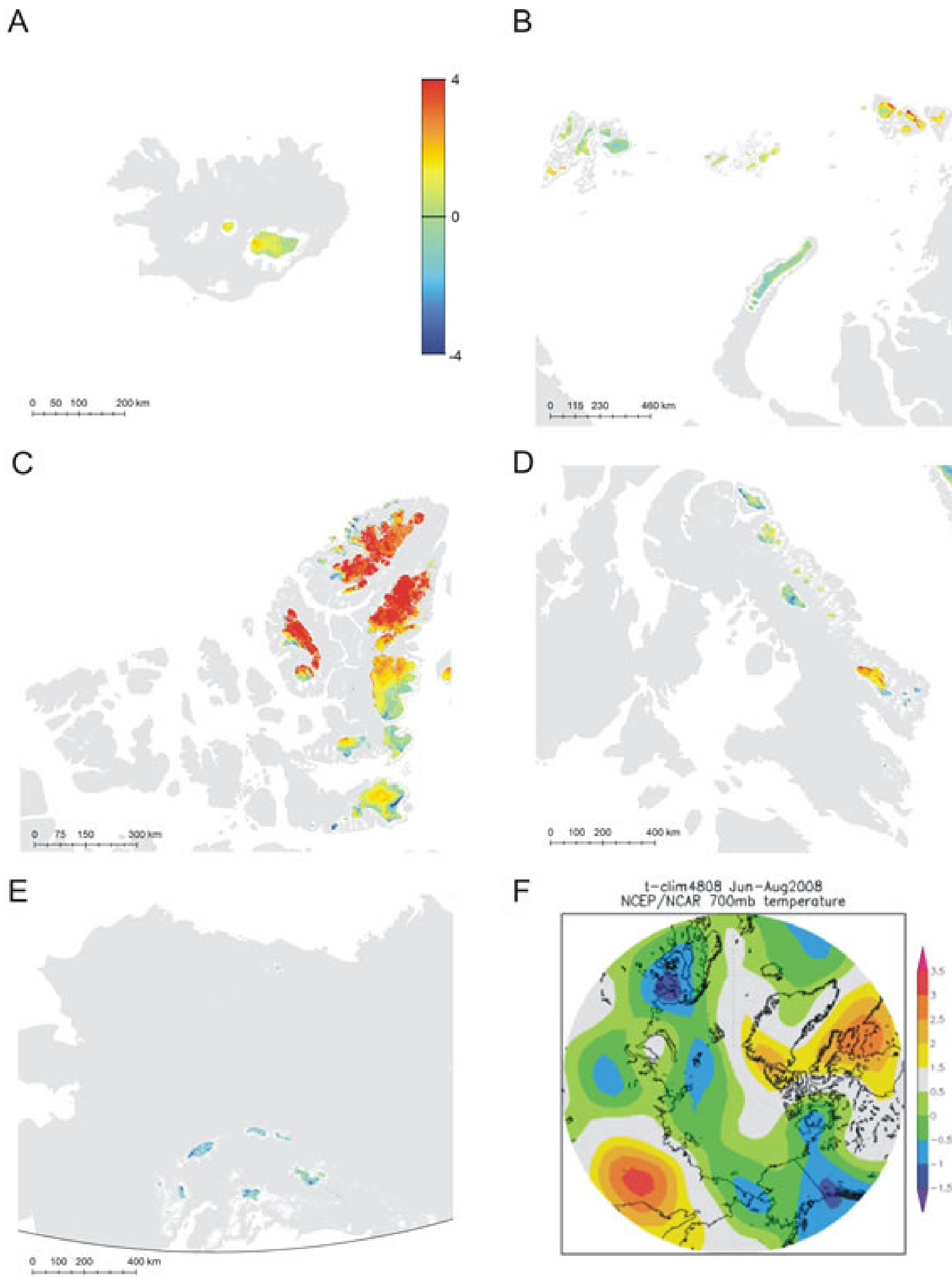

Figure G1. 2008 standardised melt duration anomalies derived from QuikScat for glaciers and ice caps in (a) Iceland, (b) the Eurasian Arctic, (c) the Queen Elizabeth Islands, (d) Baffin and Bylot Islands, and (e) Alaska. (f) Anomalies in JJA 2008 mean air temperature (degrees Celsius) at 700 hPa relative to 1948–2008 climatology from the NCEP/NCAR Reanalysis.

Table G1. Melt onset and freeze-up dates

Region	Sub-Region	Latitude (N)	Longitude (E)	JJA 700 hPa T Anomaly	2008 Rank	Sep-May Ppt Anomaly	2008 Rank	Melt Onset Anomaly	Freeze-up Anomaly	Melt Duration Anomaly
				(deg C)	(/60)	(mm)	(/60)	days	days	days
Arctic Canada	N. Ellesmere Island	80.6–83.1	267.7–294.1	2	4	12.3	10	-1.8	9.8	19.3
	Axel Heiberg Island	78.4–80.6	265.5–271.5	1.67	5	0	30	-2.9	11.4	17.6
	Agassiz Ice Cap	79.2–81.1	278.9–290.4	2.11	3	-9.2	44	5.4	24.0	22.5
	Prince of Wales Icefield	77.3–79.1	278–284.9	1.77	7	-11.4	42	2.1	7.8	10.2
	Sydkap	76.5–77.1	270.7–275.8	1.53	6	-58.5	59	3.0	3.8	1.4
	Manson Icefield	76.2–77.2	278.7–282.1	1.71	7	-62.5	56	6.4	5.7	0.0
	Devon Ice Cap	74.5–75.8	273.4–280.3	1.47	6	-8	33	0.8	-0.8	5.8
	North Baffin	68–74	278–295	1.97	2	12.4	17	-26.9	-14.4	4.9
	South Baffin	65–68	290–300	2.39	1	5.9	25	-2.8	-1.6	-1.1
Eurasian Arctic	Severnaya Zemlya	76.25–81.25	88.75–111.25	-0.36	41	38.9	17	-0.2	13.4	10.6
	Novaya Zemlya	68.75–78.75	48.75–71.25	0.29	24	78	6	21.5	-5.3	-4.2
	Franz Josef Land	80–83	45–65	-0.77	46	110	3	8.4	-2.4	6.1
	Svalbard	76.25–81.25	8.75–31.25	0.13	31	58.5	7	-6.6	-2.8	-0.8
	Iceland	63–66	338–346	0.13	27	-29.3	46	-4.2	-14.4	6.5
Alaska	SW Alaska	60–65	210–220	-0.33	40	117.4	14	3.5	-15.6	-17.7
	SE Alaska	55–60	220–230	-0.91	50	237	5	*	*	*

The total ice shelf area in Arctic Canada decreased by 23% in summer 2008 (Mueller et al., 2008). The Markham ice shelf disappeared completely and the Serson ice shelf lost 60% of its area. 90% of Arctic ice shelf area has been lost in the past century. Several fjords on the north coast of Ellesmere Island are now ice-free for the first time in 3000–5500 years (England et al., 2008).

Acknowledgements

We thank D. Burgess, G. Cogley, P. Glowacki, J. Jania, S. O'Neel, D. Puczko, A. Arendt and S. Luthcke for data contributions.

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Greenland

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October 19, 2009

Summary

An abnormally cold winter across the southern half of Greenland led to substantially higher west coast sea ice thickness and concentration. Even so, record-setting summer temperatures around Greenland, combined with an intense melt season (particularly across the northern ice sheet), led the 2008 Greenland climate to be marked by continued ice sheet mass deficit and marine-terminating ice disintegration.

Regional surface temperatures

Temperature anomalies were mixed and exhibited seasonal variability (Fig. 5.17). Annual mean temperatures for the whole ice sheet were +0.9°C, but were not abnormal, given a rank of 23 of 51 years over the 1958–2008 period (Box et al. 2006). Persistent warm anomalies were evident over the northern ice sheet in all seasons. Temperatures were abnormally cold over the southern ice sheet in winter. Coastal meteorological stations around Greenland with a consistent 51-yr period (1958–2008) (Cappelen 2009) indicate a record-setting warm summer in 2008. The Upernavik (Nuuk) summer temperature was the warmest (second warmest) on record since 1873, respectively.

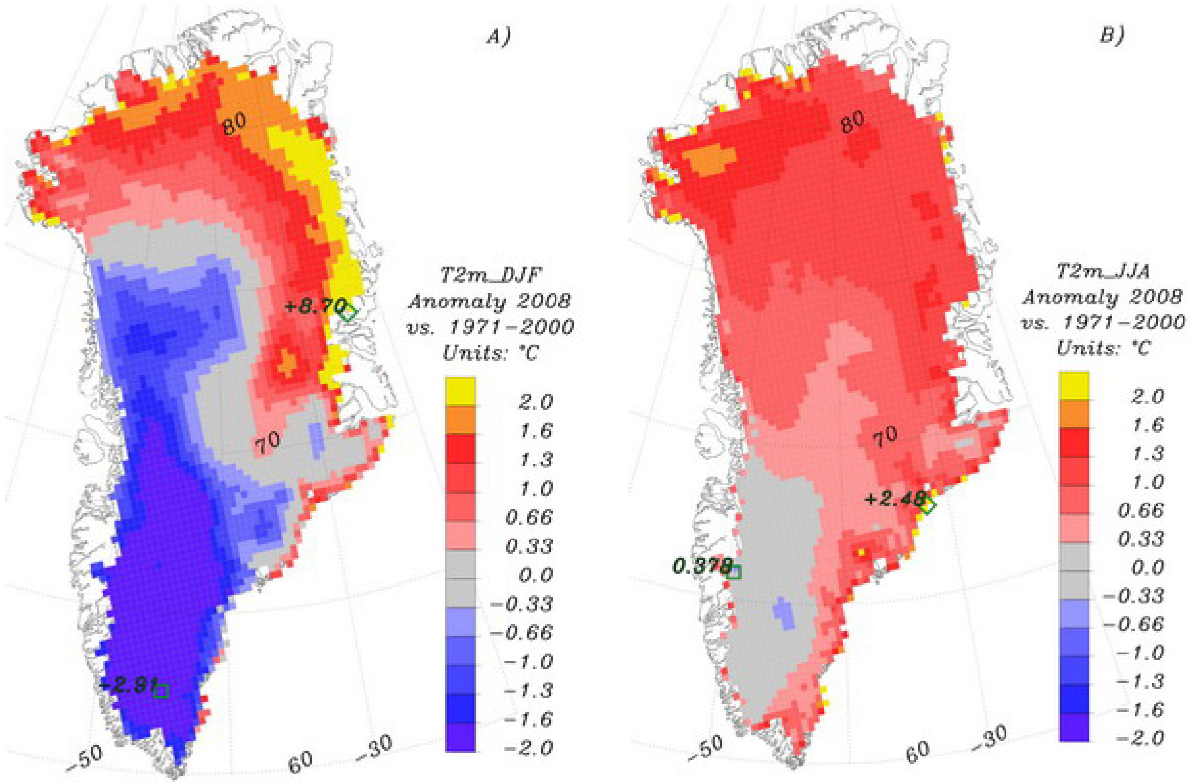

Figure G1. (a) winter and (b) summer near-surface (2 m) air temperature anomalies with respect to the 1971–2000 base period, simulated by Polar MM5 after Box et al. (2006).

Table G1. 2008 Summer 700-hPa temperature and winter precipitation anomalies (relative to 1948–2008 NCEP reanalysis means) for glaciated regions of the Arctic (excluding Greenland). Inferred sign of surface mass balance is based on comparison of historical mass balance records for each region with NCECEP reanalysis temperature and precipitation anomalies. Anomalies in melt duration and the timing of melt onset and freeze-up (relative to 2000–04 climatology) derived from QuikSCAT data. For timing, negative anomalies indicate an earlier-than-normal date.

Region	Sub-region	Latitude (°N)	Longitude (°E)	JJA 700-hPa T Anomaly	2008 Rank	Sep–May Ppt Anomaly	2008 Rank	Inferred Surface Balance	Melt Onset Anomaly	Freeze-up Anomaly	Melt Duration Anomaly
				(°C)	(*N* = 60)	(mm)	(*N* = 60)		days	days	days
Arctic Canda	North Ellesmere Island	80.6–83.1	267.7–294.1	2	4	12.3	10	--	−1.8	9.8	19.3
	Axel Heiberg Island	78.4–80.6	265.5–271.5	1.67	5	0	30	--	−2.9	11.4	17.6
	Agassiz Ice Cap	79.2–81.1	278.9–290.4	2.11	3	−9.2	44	--	5.4	24.0	22.5
	Prince of Wales Icefield	77.3–79.1	278–284.9	1.77	7	−11.4	42	--	2.1	7.8	10.2
	Sydkap	76.5–77.1	20.7–275.8	1.53	6	−58.5	59	--	3.0	3.8	1.4
	Manson Icefield	76.2–77.2	278.7–282.1	1.71	7	−62.5	56	--	6.4	5.7	0.0
	Devon Ice Cap	74.5–75.8	273.4–280.3	1.47	6	−8	33	--	0.8	−0.8	5.8
	North Baffin	68–74	278–295	1.97	2	12.4	17	--	−26.9	−14.4	4.9
	South Baffin	65–68	290–300	2.39	1	5.9	25	--	−2.8	−1.6	−1.1
Eurasian Arctic	Severnaya Zemlya	76.25–81.25	88.75–111.25	−0.36	41	38.9	17	+	−0.2	13.4	10.6
	Novaya Zemlya	68.75–78.75	48.75–71.25	0.29	24	78	6	+	21.5	−5.3	−4.2
	Franz Josef Land	80–83	45–65	−0.77	46	110	3	++	8.4	−2.4	6.1
	Svalbard	76.25–81.25	8.75–31.25	0.13	31	58.5	7	+	−6.6	−2.8	−0.8
Iceland		63–66	338–346	0.13	27	−29.3	46	–	−4.2	−14.4	6.5
Alaska	SW Alaska	60–65	210–220	−0.33	40	117.4	14	+	3.5	−15.6	−17.7
	SE Alaska	55–60	220–230	−0.91	50	237	5	++	*	*	*

Upper-air temperatures

Upper-air sounding data available from the Integrated Global Radiosonde Archive (Durre et al. 2006) indicate a continued pattern of lower tropospheric warming and lower stratospheric cooling

1964-onward (Box and Cohen 2006). Lower tropospheric warm anomalies in all seasons, particularly in spring along western Greenland, were accompanied by relatively small midtropospheric cool anomalies. Winter tropopause temperatures (200 hPa) were above normal. Lower stratospheric (above 100 hPa) temperatures were lower than normal.

Surface melt extent and duration

Passive (SMMR and SSM/I, 1979–2008) and active (QuikSCAT, 2000–08) microwave remote sensing (Bhattacharya et al. 2009, submitted to Geophys. Res. Lett.; Liu et al. 2005) indicate abnormally high melt duration over the north and northeast ice sheet and along the east and west coasts above Greenland's most productive three outlet glaciers in terms of ice discharge into the sea: Kangerlussuaq; Helheim; and Jakobshavn (Fig.G2). Lower-than-normal melt duration is evident over much of the upper elevations of the ice sheet. New records of the number of melting days were observed over the northern ice sheet, where melting lasted up to 18 days longer than previous maximum values. Anomalies near the west coast are characterized by melting up to 5–10 days longer than the average (Tedesco et al. 2008).

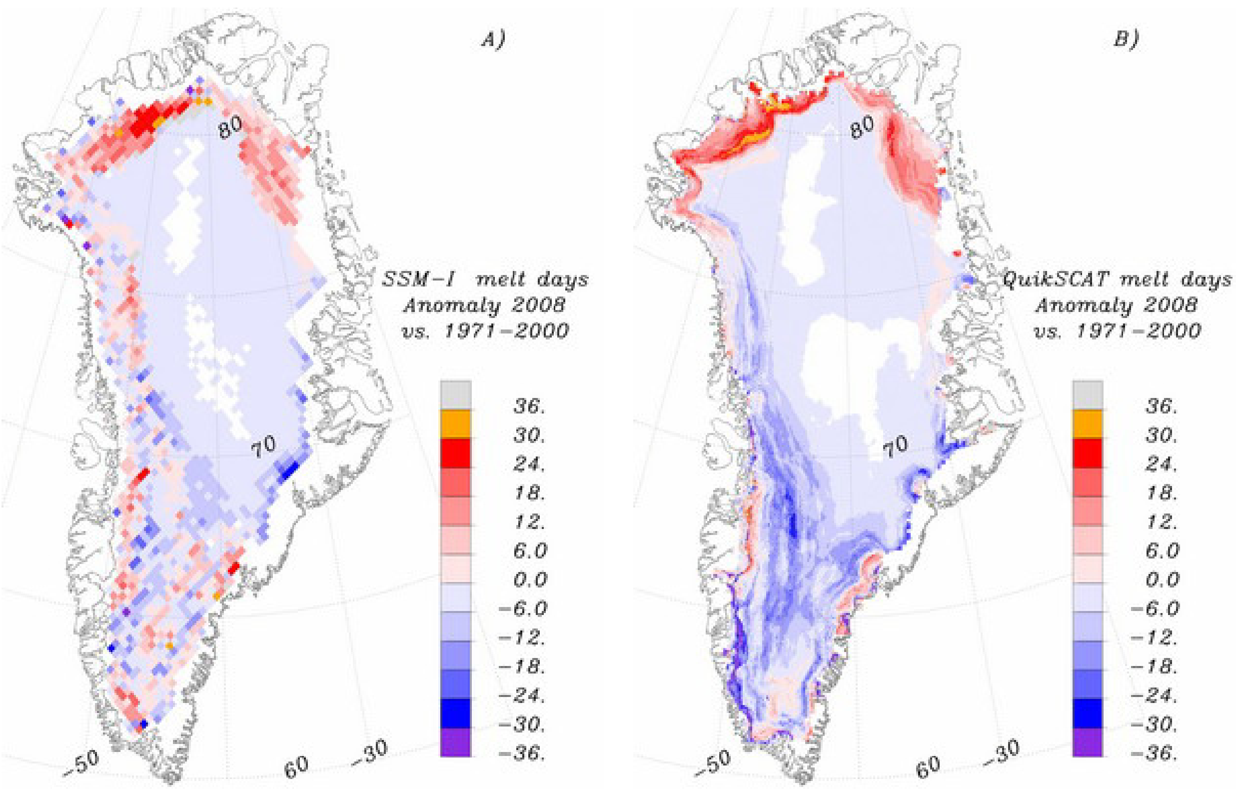

Figure G2. 2008 Greenland ice sheet surface melt duration anomalies relative to the 1989–2008 base period based on (a) SSM/I and (b) QuikSCAT (2000–08 base period), after Bhattacharya et al. (2009, submitted to Geophys. Res. Lett.).

The average daily melt extent, after Mote and Anderson (1995) and Mote (2007), for 2008 was 424,000 km^2, about 2.4% greater than the 1989–2008 average of 414,000 km^2, representing the lowest average melt extent since 2001. Significantly more melt occurred in 2008 in the northeast (45.6% greater than the 1989–2008 average) and northwest (29.7%), but less occurred in the two east-central regions (−16.8% and −25.4%) and in the southeast (−21.1%). Melt extent in 2008 was also above the 1979–2007 average. The trend in the total area of melt during 1979–2008 is approximately +15,900 km^2 yr^{-1} and is significant at the 95% confidence interval ($p < 0.01$).

Precipitation anomalies

Annual PT anomalies in 2008, determined using Polar MM5 data assimilation modeling (Bromwich et al. 2001; Cassano et al. 2001; Box et al. 2006), were positive (negative) up to 750 mm (−250 mm) over the eastern (western) ice sheet, respectively. More PT than normal occurred in isolated areas in extreme southeast, east, north, and northwestern Greenland. The overall anomaly indicated approximately 41 Gt more PT than normal for the 1971–2000 standard normal period.

Surface albedo

Melt season (day 92–274) surface albedo anomalies, derived using the Liang et al. (2005) algorithm applied to daily cloud-free MODIS imagery, indicate a lower surface albedo around the ablation zone (except the east ice sheet) (Fig. G3) resulting from the combined effect of the positive summer surface melt intensity anomaly and, in most areas, less winter snow coverage. A positive albedo anomaly is evident for the ice sheet accumulation zone and is consistent with above-average solid precipitation and/or less-than-normal melting/snow grain metamorphism.

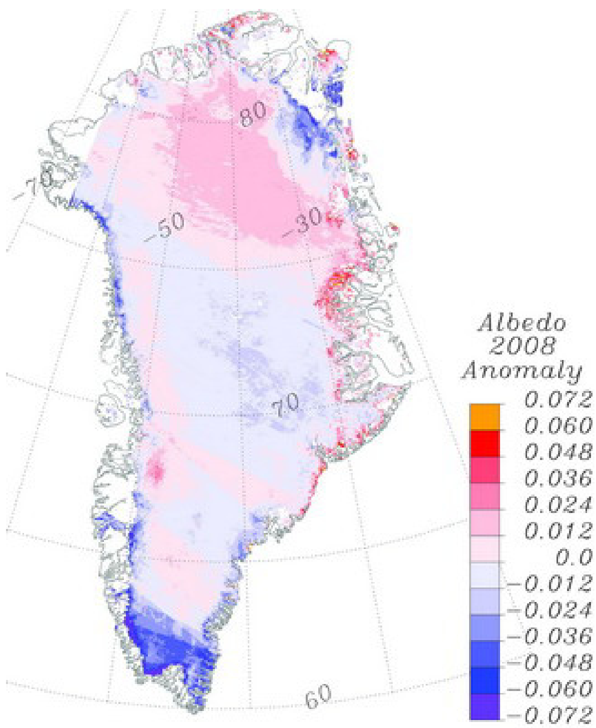

Figure G3. Surface albedo anomaly Jun–Jul 2008 relative to a Jun–Jul 2000–08 base period.

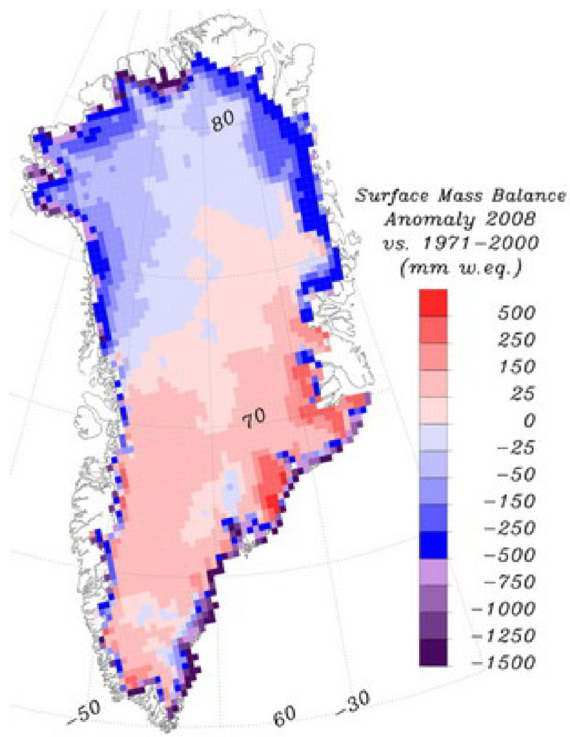

Figure G4. 2008 surface mass balance anomalies with respect to the 1971–2000 base period, simulated by Polar MM5 after Box et al. (2006).

Surface mass balance

Polar MM5 climate data assimilation model runs spanning 51 years (1958–2008), calibrated by independent in situ ice-core observations (Bales et al. 2001; Mosley-Thompson et al. 2001; Hanna et al. 2006) and ablation stakes (van de Wal et al. 2006), indicate that 2008 total precipitation and net snow accumulation was slightly (6%–8%) above normal (Table G2). In accordance with a +0.9°C 2008 annual mean surface temperature anomaly, the fraction of precipitation that fell as rain instead of snow, surface meltwater production, and meltwater runoff were 142%–186% of the 1971–2000 mean. Consequently, and despite 6%–9% (39–50 Gt) more snow accumulation than normal, the surface net mass balance was substantially (145 Gt) below normal. 2008 surface mass balance ranked ninth-least positive out of 51 years (1958–2008).

Table G2. Greenland ice sheet surface mass balance parameters: 2008 departures from 1971–2000 average (adapted from Box et al. 2006). Estimates by Hanna et al. (2008) are included for comparison.

	Box			Hanna		
	Mean (1971–2000)	% of normal	2008 Anomaly (Gt)	Mean (1971–2000)	% of normal	2008 Anomaly (Gt)
Total Precipitation	710.7	105%	38.5	624.16	108%	52
Liquid Precipitation	16.8	142%	7.1	27.01	147%	13
Surface Water Vapor Flux	66.7	100%	−0.2	40.59	74%	−11
Blowing Snow Sumblimation	39.6	99%	−0.3			
Snow Accumulation	604.5	106%	39.0	556.56	109%	50
Meltwater Volume	330.1	159%	194.1	333.95	133%	110
Meltwater Runoff	214.9	186%	184.3	277.91	142%	116
Surface Mass Balance	389.6	63%	−145.3	305.66	83%	−53
Mean T	−19.0		0.9	−21.4		1.1
AAR	0.920	0.905%	−0.087	0.859	0.933%	−0.007

Surface mass balance anomalies indicate a pattern of increased marginal melting with noteworthy departures in excess of 1-m water equivalence per year from normal across the northern ice sheet (Fig.G4). The pattern of steepening mass balance profile is consistent with observations from satellite altimetry (Zwally et al. 2005) and airborne altimetry (Krabill et al. 2000); satellite gravity retrievals (e.g., Luthcke et al. 2006); and climate projections (Solomon et al. 2007).

Marine-terminating glacier area changes

Daily surveys of Greenland ice sheet marine terminating outlet glaciers from cloud-free MODIS imagery (http://bprc.osu.edu/MODIS/) indicate that the 34 widest glaciers collectively lost 106.4 km^2 of marine-terminating ice between the end of summer 2008 and the end of summer 2009 (Figure G4). This is equivalent to an area 20% larger than Manhattan Island (87.5 km^2), New York. The largest individual glacier losses are observed at: Humboldt (-37 km^2); Zachariae Isstrom (-31 km^2); and Midgard (-16 km^2). The 2000–2009 rate (106 km^2) has been linear (R = −0.98) despite the fact that a few individual glaciers exhibit erratic annual net ice area changes. The cumulative area change from end-of-summer 2000 to 2009 is −990 km^2, an area 11.3 times that of Manhattan Island.

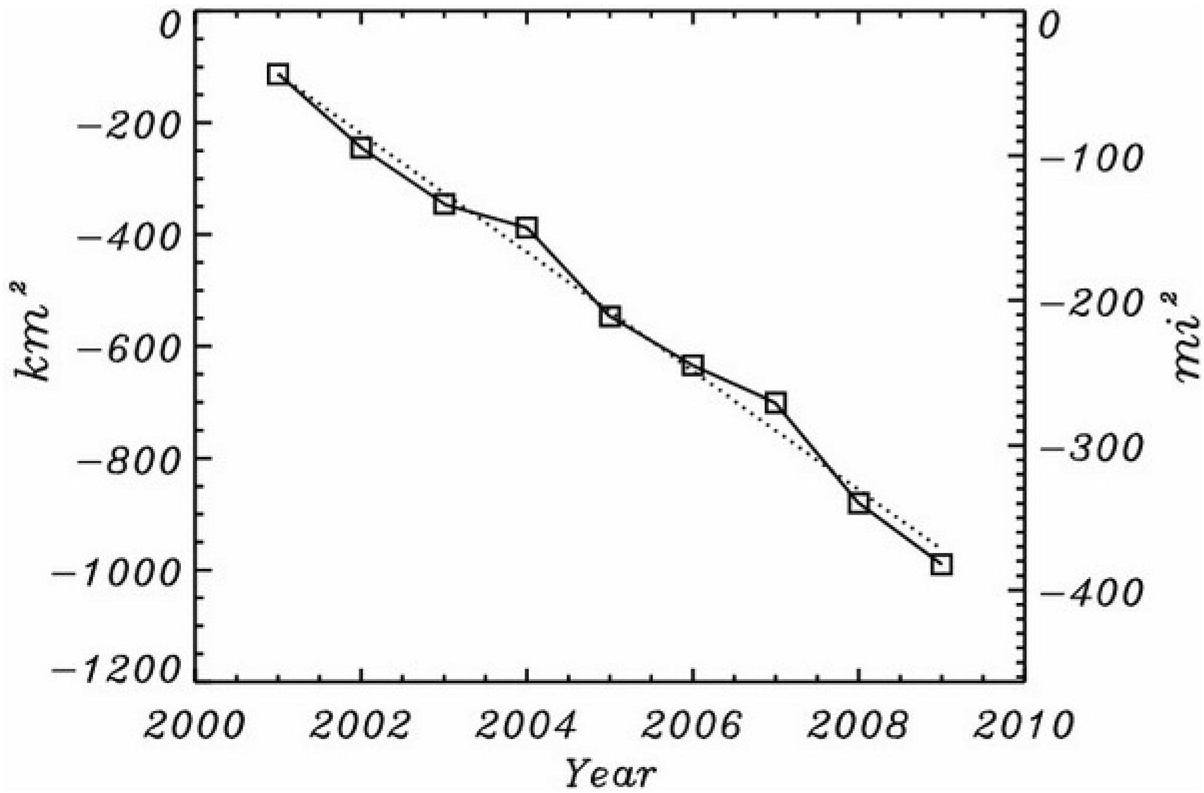

Figure G4. Cumulative annual area changes for 34 of the widest Greenland ice sheet marine-terminating outlets.

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Biology

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October 16, 2009

Summary

Broad-scale changes to Arctic wildlife populations and ecosystems illustrate the sensitivity of these systems to changing conditions, both natural and human-induced. Recent research and monitoring has shown close correlations between ocean temperatures and ecosystem states (e.g. Bering Sea fisheries) and population abundance (e.g. Murres). Also, in some instances, largely synchronous, pan-Arctic periods of abundance and scarcity suggest large-scale mechanisms (e.g. continental climate oscillations) are important determinants of population trajectories for some species. Recent examples of these close connections are the declines in wild caribou and reindeer herds across the Arctic, which are thought to be part of a long-term natural cycle. The strong linkages between arctic ecosystems and physical conditions are cause for concern as the Arctic is experiencing and expected to continue to experience rapid and wide-scale changes in temperatures and associated conditions (e.g. sea ice extent, permafrost). Broad changes in wildlife abundance and distributions are expected, with some early evidence of these changes already emerging (e.g. sea-ice dependent marine mammals such as walrus and polar bears). However, our current understanding of the response of arctic wildlife and ecosystems to both natural and human-induced change is limited. More coordinated research and monitoring is required to provide an accurate picture as to how these systems may be responding to a changing Arctic.

State of Wild Reindeer Herds

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October 19, 2009

Summary

Rangifer (wild reindeer and caribou) herds across the circumpolar north have long been characterized by periods of abundance and periods of scarcity. Recent population estimates indicate we may be entering a period of declining numbers. Populations that have been increasing at a steady rate since the early to mid 1970’s are either showing signs of peaking or beginning to decline. Figure R1 shows the current status of selected *Rangifer,* the major migratory herds and herds being monitored as part of the CARMA Network (see note on CARMA at bottom of this article). In 2009, a number of population counts were made available, which illustrates the diversity of trends across the arctic.

- On the Alaskan coastal plain the Teshekpuk Lake Herd (TLH) and the Central Arctic Herd (CAH) continued to increase by 5–7% per year. Counted in 2008 the TLH numbered 64,000 up from 45,000 in 2002. The CAH in 2008 were estimated at 67,000 up from 32,000 in 2002.
- In the Central barrens attempts to count the Beverly herd failed because only a few hundred breeding females could be found on the traditional calving grounds. The Beverly herd was last counted in 1994 when the population was estimated at 276,000 animals.
- The Bathurst Caribou herd was counted in 2009 and, although an estimate is not finalized, biologists believe the count will be less than 50,000 animals down from a population peak of over 470,000 in 1986.
- Across the north a number of herds were counted in 2009 or are scheduled to be counted in 2010 in an effort to more closely monitor the apparent declines that are occurring.

Most feel the general declines that the north is experiencing are part of a natural cycle. However during this population scarcity many are concerned that the increased threats of climate change, increased industrial expansion in the north and the increased sophistication and mobility of harvesters will require more careful monitoring and analysis of population response. The CircumArctic *Rangifer* Monitoring and Assessment (CARMA) Network (http://www.rangifer.net/carma/) was formed in response for a need to cooperate and coordinate monitoring efforts across the north. The Network is taking advantage of the International Polar Year initiative to increase its monitoring and assessment activities.

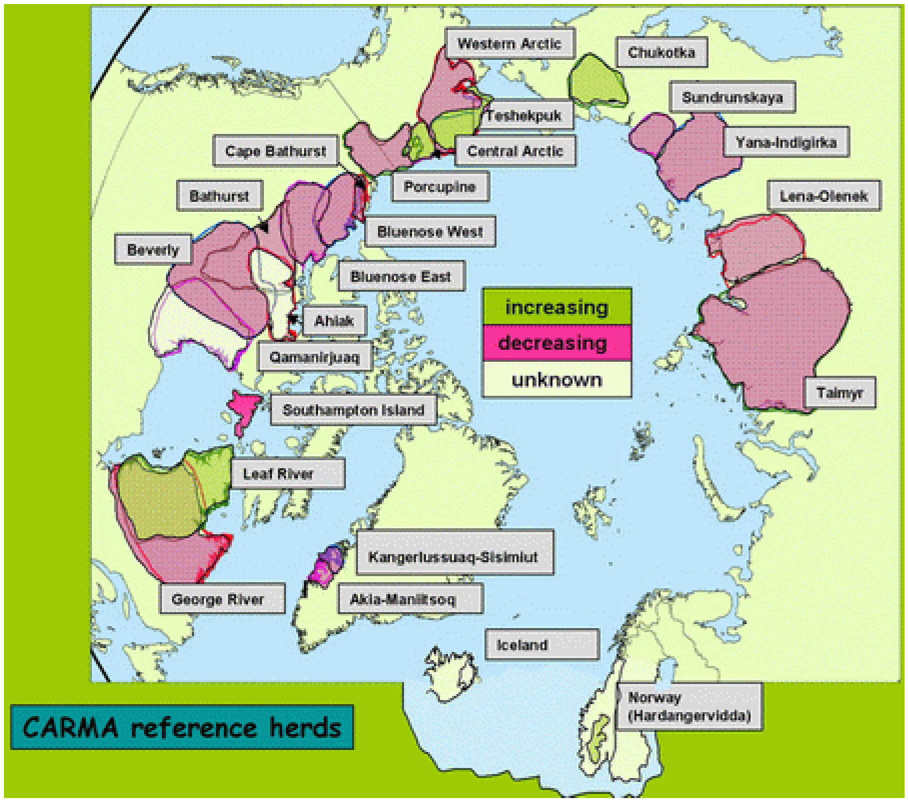

Figure R1. Current status of the main migratory herds across the circumpolar north.

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Marine Mammals

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October 19, 2009

Figure M1. Marine mammals found in the Arctic. Clockwise from the upper left: Beluga whales, Narwhal, Ringed seal, Walrus, Bowhead whale, Bearded Seal, and center, Polar Bear.

A variety of marine mammals can be found in the Arctic at least seasonally. Seven species are present in the Arctic year-round and are often associated with sea ice—bowhead whale, beluga whale, narwhal, ringed seal, bearded seal, walrus, and polar bear. All seven of these species are important top predators within Arctic marine ecosystems. As such they may serve as sentinels of Arctic climate change, with changes in their status reflecting ecosystem-wide perturbations[1]. Table M1 summarizes current knowledge regarding the abundance and trends of these species. Unfortunately, abundance estimates are not available for one or more populations of most species, and trends are unknown for even more populations. Further, some of the available estimates are based on data from the 1990s or earlier and, therefore, are out of date. It is clear, even from this limited information, that several populations of Arctic marine mammals are quite small (e.g., Ungava Bay and Cook Inlet belugas, Lake Saimaa ringed seals, and several stocks of polar bears each have 400 or fewer animals), and this raises concerns about the potential impact of catastrophes such as oil spills or disease outbreaks. Also, all species with sufficient data exhibit mixed population trends, with some populations of each species increasing while others are stable or declining. The available data are not sufficient for an analysis of trends by region (e.g., to highlight regions within which populations of several species are all increasing or all declining). However, it is likely that species within a region will exhibit different trends because they occupy very different ecological niches, ranging from the bowhead whale that filters zooplankton out of the water to the polar bear that hunts seals on the sea ice (Table M2).

A comprehensive assessment of the status of Arctic marine mammals must consider current population demography and dynamics as well as the resistance or resilience of each species to current and projected threats. Arctic marine mammals appear to be in a tenuous position—they are adapted to life in seas that are at least seasonally ice-covered, and the extent of summer ice cover is rapidly diminishing[41]. These species are long-lived and reproduce slowly and, although they have persisted through ice ages and interglacial periods in the past, it is unclear how quickly they can adapt to rapid changes in habitat. The impacts of reduced sea ice vary depending on the ecological relationship between each species and sea ice[41] (Table M2). A recent special publication of Ecological Applications provides a comprehensive review of the likely impacts of climate change on Arctic marine mammals[42], and other reviews discuss impacts of climate change on marine mammals broadly at a global scale[43] and in more detail for the North Atlantic Arctic[44].

Although assessment of future impacts is by its very nature speculative, currently observed impacts on polar bears and walruses indicate that Arctic marine mammals will almost certainly be affected by the predicted changes in Arctic marine ecosystems [45]. Reduced sea ice has already been implicated in lower body condition and reduced survival of polar bears in western Hudson Bay, and similar impacts are likely elsewhere as sea ice breaks up earlier and bears are forced to fast on shore longer [46,47]. The record sea ice retreat of 2007 caused Pacific walruses to haul out along the shores of Alaska and Russia in unusually large numbers and in new locations [48]. The immediate impact of this redistribution was an increase in trampling deaths as walruses on shore stampeded in response to terrestrial disturbances [48]. Over the long-term, walruses could deplete nearshore benthic resources if they are forced to use land haul-out sites exclusively in the future. Similar shifts in the seasonal distribution of all Arctic marine mammals are likely. For example, species that are strongly tied to sea ice habitats, such as the polar bear and ringed seal, may be limited in the future to areas with sea ice refugia (e.g., summer sea ice is predicted to persist longer in the Canadian Arctic Archipelago than elsewhere), whereas sub-Arctic or migratory species may be able to access areas where sea ice had previously excluded them[41]. Further, species or populations that either migrate with the sea ice edge or make forays to the ice edge from coastal areas may have to travel farther and expend more energy as the summer sea ice edge retreats farther from the coast and from the location of the winter ice edge [49,50].

In addition to the more obvious impacts that changes in the distribution and quality of habitat will have on the distribution of Arctic marine mammals, early spring rains could cause ringed seal lairs to collapse, exposing their pups to hypothermia and increased predation by polar bears and arctic foxes [51], and it has been suggested that increased variability in sea ice and weather conditions could result in more frequent ice entrapments of narwhals and belugas [52,53]. Further, changes in the seasonality of ice retreat could result in changes in the timing and location of phytoplankton blooms (e.g., associated with the melting ice edge or in open water following ice retreat), which in turn could influence both the total amount of primary production and the allocation of that production among pelagic and benthic food webs [39]. Of course, in addition to environmental impacts, reduced sea ice will make the Arctic more accessible for some species (e.g., gray whales[1]) and for human activities, some of which could impact marine mammals (e.g., oil spills, habitat alteration, prey removals, contaminants, and ship strikes). Also, all of these species are harvested for subsistence, with varying degrees of regulation among populations and regions.

Given the threats (both observed and predicted) facing marine mammals, there is justifiable cause for concern regarding populations that are small or declining, as well as those for which information is insufficient. Expanded and accelerated research and monitoring efforts will be necessary to detect changes in the status of Arctic marine mammal populations and to identify the causes of those changes in time to allow developing problems to be addressed [54,55,56].

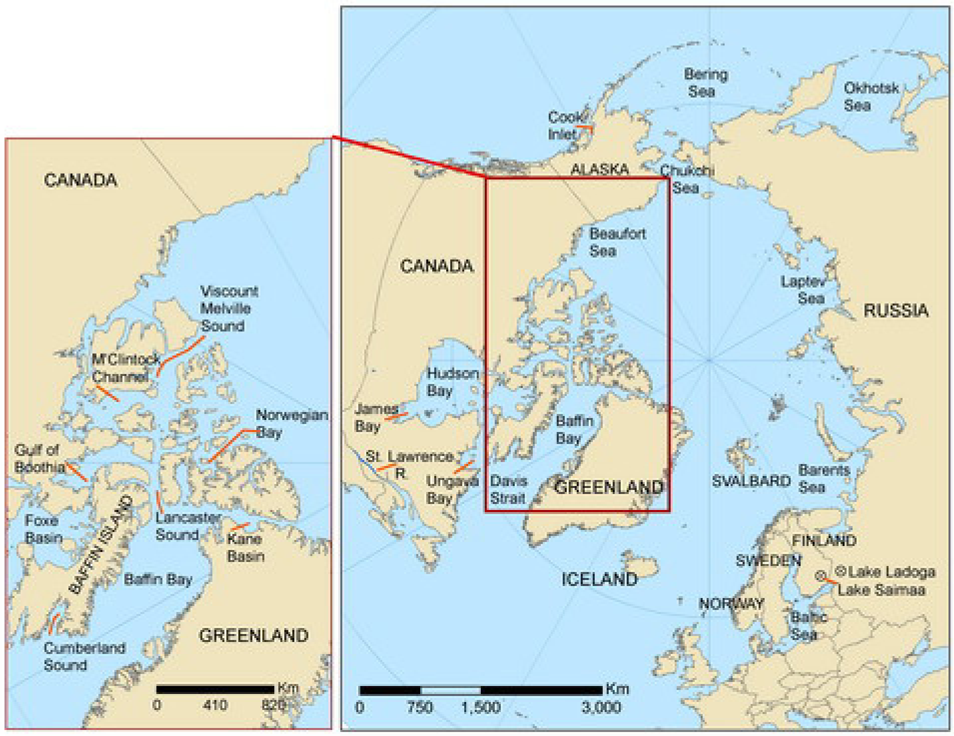

Figure M2. Map of the Arctic with place names referred to in the text or in Table M1.

Table M1. Current abundance and trends of Arctic marine mammal species. Information on abundance, trends, and most recent data (year) are summarized by biological stock, except for ringed seals, bearded seals, and walruses, whose stock structure is unknown (see table footnotes). Figure M2 indicates the locations of place names referred to here. Citation numbers refer to literature cited.

Species	Stock	Abundance	Year	Trend	Citation(s)
Bowhead whale	Bering-Chukchi-Beaufort Seas	10,500	2001	increasing	2
	E. Canada-W. Greenland	6,300	2002–2004	increasing	3,4
	Spitsbergen	unknown	—	unknown	5
	Okhotsk Sea	<400	1979	unknown	5
Beluga whale	Cook Inlet	380	2007	stable	6
	Eastern Bering Sea	18,100	2000	unknown	7
	Bristol Bay	3,300	2005	increasing	6
	Eastern Chukchi Sea	3,700	1989–1991	unknown	6
	Eastern Beaufort Sea	39,300	1992	unknown	6
	Foxe Basin	1,000	1983	unknown	8
	Western Hudson Bay	57,300	2004	unknown	9
	Southern Hudson Bay	1,300	1987	unknown	10
	James Bay	4,000	2004	unknown	11
	St. Lawrence River	1,200	2005	stable	12

	Eastern Hudson Bay	4,300	2004	declining	13
	Ungava Bay	<50	2007	unknown	14
	Cumberland Sound	1,500	1999	increasing	15
	E. High Arctic-Baffin Bay	21,200	1996	stable	16
	West Greenland	7,900	1998–1999	unknown	17
	3 stocks in Okhotsk Sea	18–20,000	1987	unknown	18
	11 additional stocks	unknown	—	unknown	
Narwhal	Canadian High Arctic	>60,000	2002–2004	unknown	19
	Northern Hudson Bay	3,500	2000	unknown	20
	West Greenland	2,000	1998–999	unknown	21,22
	East Greenland	>1,000	1980–1984	unknown	21,23
Ringed seal[a]	Arctic subspecies	~2.5 million	1970s	unknown	24
	Baltic Sea subspecies	5,000–8,000	1990s	mixed	25
	Lake Saimaa subspecies	280	2005	increasing	26
	Lake Ladoga subspecies	3,000–5,000	2001	unknown	27
	Okhotsk Sea subspecies	>800,000	1971	unknown	24
Bearded seal[b]	Bering-Chukchi Seas	250–300,000	1970s	unknown	28
	Canadian waters	190,000	1958–1979	unknown	29
	Atlantic and Russian Arctic	unknown	—	unknown	
	Okhotsk Sea	200–250,000	1968–1969	unknown	28
Walrus[c]	Bering-Chukchi Seas	~201,000	1990	unknown	30
	Atlantic subspecies	18–20,000	2006	mixed	31,32,33,34
	Laptev Sea	4,000–5,000	1982	unknown	35
	Other regions	unknown	—	unknown	
Polar bear[d]	Chukchi Sea	2,000	1993	unknown	36
	Southern Beaufort Sea	1,500	2006	declining	36
	Northern Beaufort Sea	1,200	1986	stable	36
	Viscount Melville Sound	220	1992	increasing	36
	McClintock Channel	280	2000	increasing	36
	Norwegian Bay	190	1998	declining	36
	Lancaster Sound	2,500	1998	stable	36
	Gulf of Boothia	1,500	2000	stable	36
	Foxe Basin	2,200	1994	stable	36
	Western Hudson Bay	940	2004	declining	36
	Southern Hudson Bay	1,000	1988	stable	36
	Baffin Bay	2,100	1998	declining	36
	Davis Strait	1,700	2004	unknown	36
	Kane Basin	160	1998	declining	36
	Barents Sea	2,700	2004	unknown	37
	Laptev Sea	4,000–5,000	1993	unknown	36
	3 other stocks	unknown	—	unknown	

[a] Ringed seal stock structure unknown; information summarized for five recognized subspecies.
[b] Bearded seal stock structure unknown; information summarized for geographic regions.
[c] Walrus stock structure unknown; information summarized for Atlantic subspecies and geographic regions for Pacific subspecies.
[d] Recent analysis of genetic, ecological and life history data from Canadian polar bears suggests that their stock structure may need to be revised [38].

Table M2. Key Arctic marine mammal species ecology		
Species	**Primary Diet** [39]	**Relationship with Sea Ice Habitat** [40]
Bowhead whale	Zooplankton (filter feeder)	Forage in productive marginal ice zone
Beluga whale	Diverse fishes and invertebrates	Refuge from predation? Access ice-associated prey
Narwhal	Ice-associated and benthic fishes (deep diver)	Forage in areas of very dense ice
Ringed seal	Diverse fishes and invertebrates	Resting and nursing platform Access ice-associated prey
Bearded seal	Benthic invertebrates	Resting and nursing platform Access to benthic foraging grounds
Walrus	Benthic invertebrates	Resting and nursing platform Access to benthic foraging grounds
Polar bear	Seals (primarily ringed) and other marine mammals	Hunting platform

Acknowledgments

The information summarized here was collected through the hard work of countless Arctic researchers whose contributions to this report far outweigh the author's own. Kit Kovacs, Randy Reeves, and their colleagues in the Pinniped and Cetacean Specialist Groups of the International Union for Conservation of Nature (IUCN) provided invaluable help by identifying key sources of information for Arctic marine mammal stocks. Joselyd Garcia compiled the information presented in Table M1, and Mina Innes produced Figure M1. This report was improved by comments on earlier versions by Mike Cameron, Mike Gill, Bob Gisiner, Kit Kovacs, Kristin Laidre, Sue Moore, Jim Overland, Tim Ragen, Jackie Richter-Menge, Randy Reeves, Dave Rugh, Michael Svoboda, and anonymous reviewers.

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Bowhead: Julie Mocklin, National Marine Mammal Lab, AFSC, NMFS, NOAA
Beluga: Laura Morse, National Marine Mammal Lab, AFSC, NMFS, NOAA
Narwhal: Kristin Laidre, University of Washington
Ringed seal: Brendan P. Kelly, University of Alaska Southeast
Bearded seal: Ian Stirling, Environment Canada
Walrus: Ian Stirling, Environment Canada
Polar bear: Ian Stirling, Environment Canada
Collage created by Tracey Nakamura, NOAA/PMEL

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Murres

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September 9 , 2009

Introduction

The two species of murres (N. America)/guillemots (Europe), *Uria lomvia* (Thick-billed Murre) and *U. aalge* (Common Murre), both have circumpolar distributions, the former breeding in Arctic and Subarctic regions, from northern Norway, Iceland, Newfoundland and the Aleutian Islands to the High Arctic, while the latter is predominantly a Subarctic and Boreal species breeding from California, the Gulf of St. Lawrence and northern Spain to the northern Bering Sea, Labrador and Bjornoya (Bear Island). In winter, *U. lomvia* occurs mostly in Arctic waters, while *U. aalge*, although overlapping extensively with *U. lomvia*, is found predominantly in subarctic and temperate waters (Figs 1 and 2). They are among the most abundant seabirds in the northern hemisphere, with both species exceeding 10 million adults (Gaston and Jones 1998).

Figure 1. St. Lawrence Island, Bering Sea, Alaska (Lisa Sheffield).

Figure 2. Murres on St. Lawrence Island, Bering Sea, Alaska (Lisa Sheffield).

Murres feed from coastal to pelagic waters, taking a wide range of small fish (<50 g) and invertebrates, including annelids, pteropod and cephalopod molluscs, and mysid, euphausiid, amphipod and decapod crustacea. Common Murres generally feed more on fish than Thick-billed Murres (Gaston and Jones 1998, Anker-Nilssen et al. 2000). Adults of both species weigh about 1 kg, can remain under water for up to 4 min and dive regularly to depths >100 m, reaching a maximum depth of ~150 m. Their diving capacity, when combined to their typical foraging radius of up to100 km from the colony, means that murres sample a relatively large volume of the marine environment around their colonies (Falk et al. 2000, Elliott et al. 2008).

Murres have proven useful indicators of environmental change in studies of population trends (Gaston et al. 2009), nestling growth (Barrett 2002, Gaston et al. 2005) and nestling diet (Osterblom et al. 2001). They breed in very large colonies of up to 1 million birds on mainland cliffs or offshore islands. In most places, they lay their eggs in the open, making breeding adults simple to count. Consequently, their population trends are relatively easy to assess and this, allied to their abundance and widespread distribution, makes them ideal subjects for circumpolar environmental monitoring. In addition, being robust birds and returning annually to the same breeding sites, they are useful platforms on which to deploy depth and temperature recorders, GPS and geolocator tags. These devices have greatly amplified the value of the birds for environmental monitoring.

Status and Trends

The sensitivity of murre populations to changes in environmental conditions has been demonstrated on a hemispheric scale in recent studies by the Seabird Working Group of CAFF

(C-Bird). Irons et al. (2008) combined population trend data from around the Arctic with information on surface sea temperature (SST) and decadal-scale oscillations, to show that both species of murre showed negative population trends where there was a large change in SST, either warmer or cooler. Colony growth was most often positive where conditions remained relatively stable (Fig. 3). More specifically, the northern species, *U. lomvia*, exhibited highest population growth where conditions warmed moderately. *U. aalge* showed highest rates of increase where things cooled moderately. In the context of global warming, this result suggests that not only the direction but the magnitude of change may be important in determining outcomes and that Common and Thick-billed Murres may not necessarily react in the same way to a given temperature change.

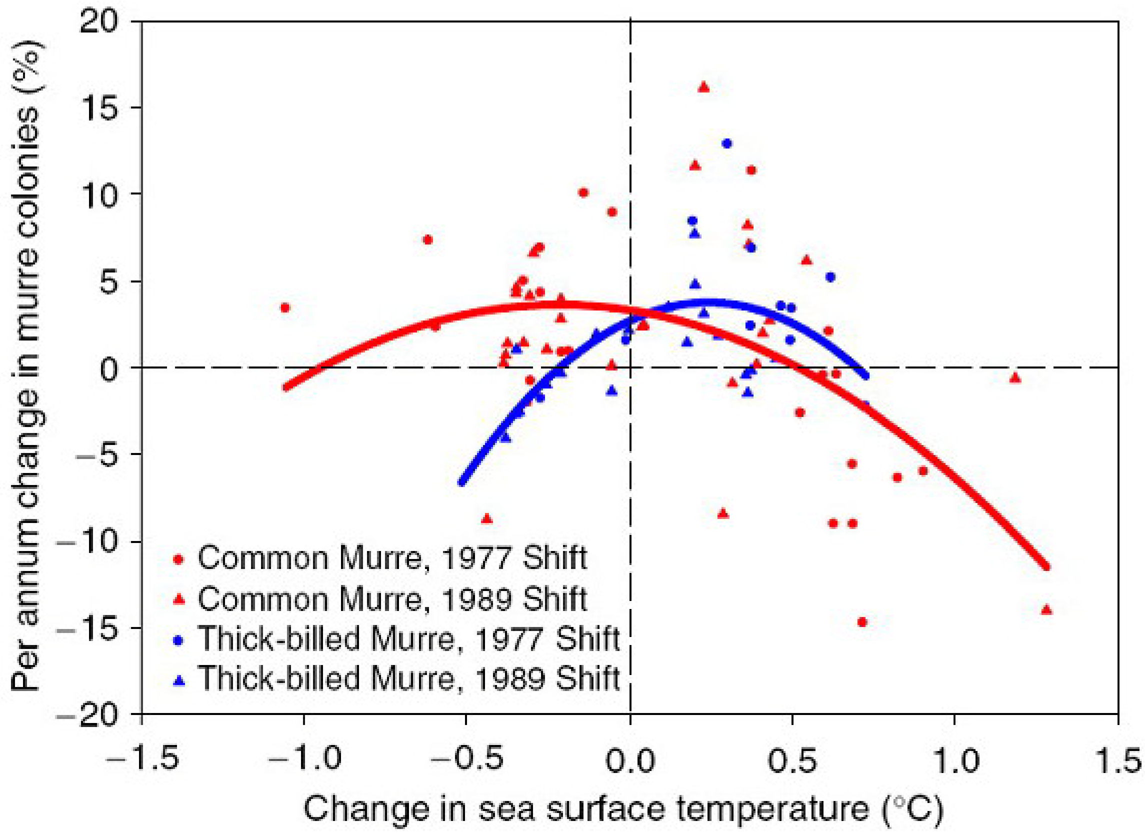

Figure 3. Relationship between per annum change in the size of murre colonies during the 12 years after the1977 climatic regime shift and during 9 years after the 1989 shift, and changes in sea surface temperatures around the colonies from one decadal regime to the next. Population data are from 32 Common and 21 Thick-billed Murre colonies, encompassing the entire circumpolar region. As 10 sites supported both species, 43 different study areas were represented. Quadratic functions were fitted to the data (Thick-billed Murres P=0.002, df=27, r2=0.370; Common Murres P<0.001, df=48, r2=0.280). Reprinted from Irons et al. 2008.

Both species have shown substantial variation in regional population trends since the 1970s. A comparison of the period from 1977–1989, when Sea Surface Temperatures (SST) in the North Pacific were generally above normal and those in the North East Atlantic generally below normal, with the period from 1989–1999 when the situation reversed, showed that populations in the North Pacific were generally decreasing during the earlier decade and increasing subsequently (Fig. 4, Irons et al. 2008). Conversely, those in the eastern Atlantic showed more variable trends. However, several European colonies were affected by widespread collapse of fish stocks in the 1980s (Vader et al. 1990). Those European colonies not affected by fish-stock collapses mostly increased up to 1989, but increases were less general between 1989–1999. Only a few colonies, principally those in the eastern Canadian Arctic, have shown consistent increases in population and no colonies have shown persistent downward trends (C-bird unpubl. data). Subsequent to 1999, regional trends have been less clear. Populations of both species in the Barents Sea have begun to recover from earlier declines related to fish stock collapse (Barrett et al. 2006). Those in Alaska and in the Canadian Arctic have been stable overall since the 1990s (Dragoo et al. 2008, Gaston et al. in press).

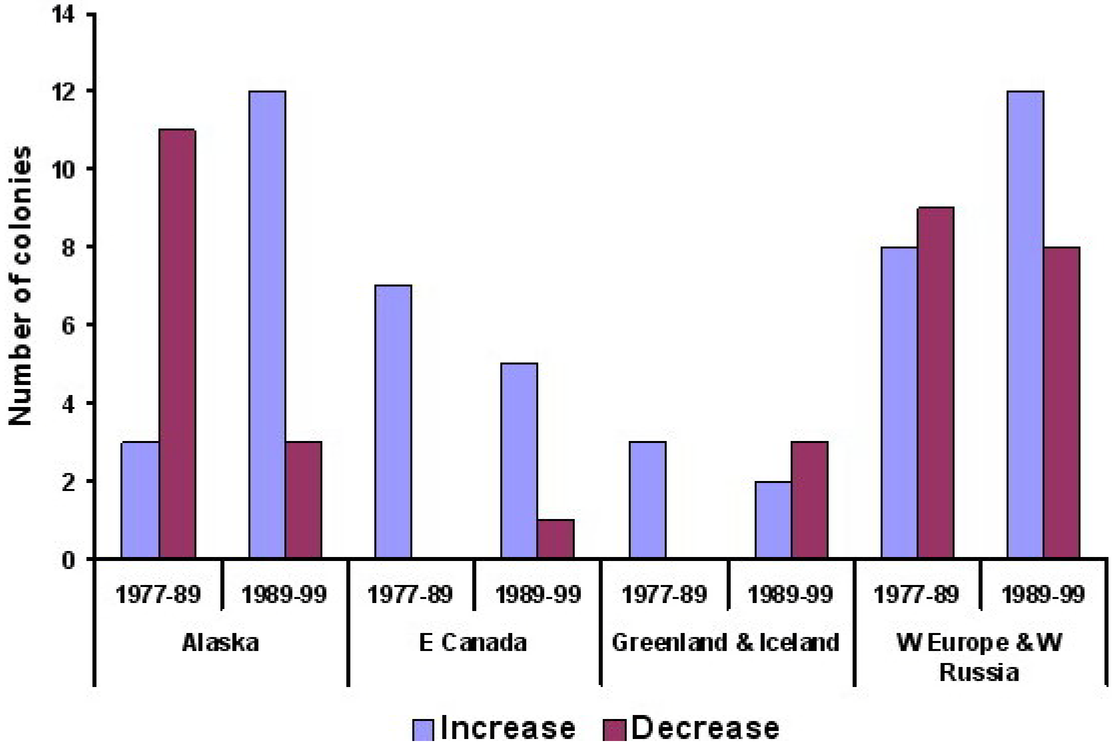

Figure 4. Number of Common and Thick-billed Murre colonies increasing or decreasing during 1977–1989 and 1989–1999.

Threats

Murres, both adults and eggs (especially lomvia), are harvested by aboriginal people and by local communities in many Arctic jurisdictions. These activities are not thought to have much impact on populations except in West Greenland, where some colonies have been substantially reduced by harvesting of adults while breeding (CAFF). Both species are highly susceptible to oiling and they are often the most numerous species killed by oil spills. They are frequently drowned in gill-nets, especially when these are set overnight (Melvin et al. 1999): hundreds of thousands were killed in salmon gill-nets off West Greenland in the 1960s (Tull et al. 1972). Although currently abundant, with few populations showing cause for alarm, climate change will pose a future problem and range contraction appears likely in the longer-term.

Knowledge Gaps

Despite substantial research and monitoring on the two species, information is generally inadequate to quantify changes in murre feeding ecology and food availability, or changes in mortality due to oil pollution, commercial fisheries, and hunting. In 1996, the Circumpolar Seabird Group reviewed conservation issues affecting murres, and produced an *International Murre*

Conservation Strategy and Action Plan to guide future international conservation efforts. The plan proposed action to assess the threats to murres from harvests, and commercial and industrial activities. The Plan also recommended further research to address the potential effects of global climate change on murre populations.

*** Note:** On “murres” vs “guillemots”. We think the use of murres is preferable because guillemot does not exclude *Cepphus* spp. when used as a collective noun.

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Fisheries in the Bering Sea

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October 5, 2009

With warm sea temperatures during 2000 to 2005, the Bering Sea was showing indications that Arctic species that require the presence of sea ice were being replaced by sub-Arctic species that don't require sea ice. This is shown schematically in the Figure F1 as a shift of the biological energy pathway that favors bottom animals (Benthic) to one favoring species that live closer to the ocean surface (Pelagic).

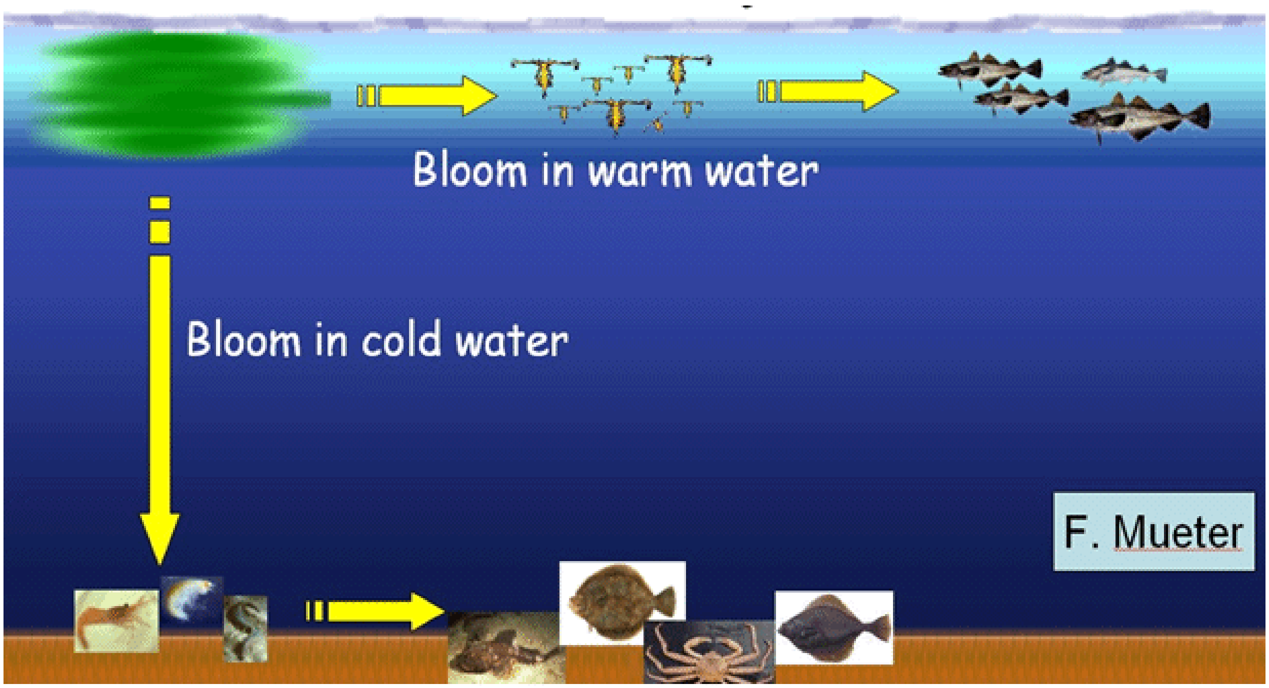

Figure F1. Bering Sea Ice shifting from Benthic to Pelagic Pathway.

However since 2005, the Bering Sea has been relatively cold with more sea ice in the winter and spring than normal. In 2008 and 2009, the winter sea ice extent in the Bering Sea was at a near record maximum, not seen since the early 1970s, and ocean temperatures were at a near record minimum (Figure F2). Under these conditions, cold water species, such as Arctic cod, have returned toward the south. At present Bering Sea climate change and ecosystem response are more effectively characterized by natural variability with multiple years of warm and cold temperatures, than by an emerging global warming trend or by an influence from the major summer sea ice losses in the Arctic Ocean proper.

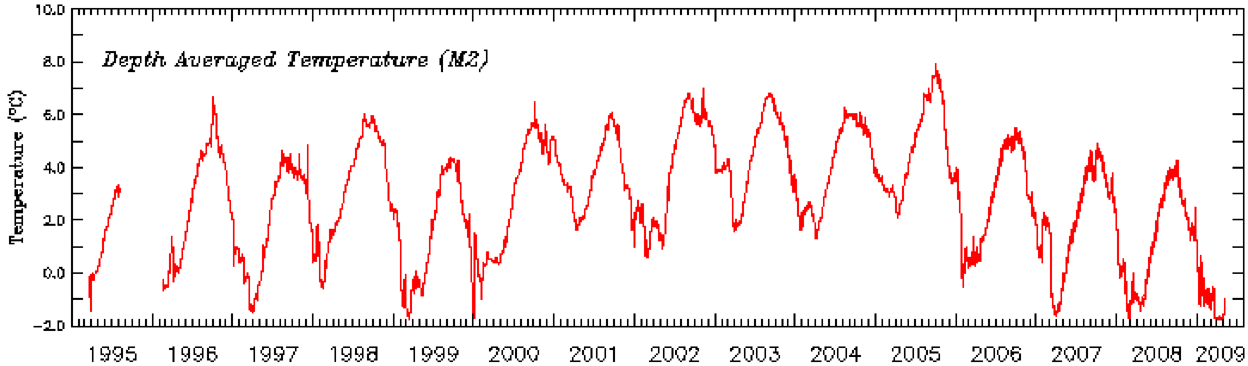

Figure F2. Southeast Bering Sea summer ocean bottom temperatures. From NOAA, P. Stabeno.

Pollock are a major economic resource from the Bering Sea. Warm temperatures and lack of sea ice have tended to favor pollock in the recent past, creating one of highest biomass for any large marine ecosystem throughout the world. The biomass for pollock in the Bering Sea and the number of new fish added each year (called recruitment) are shown in Figure F3. In recent years pollock recruitment has been low, with the decrease beginning before the return of the cold temperatures (Figure F2). The Bering Sea pollock population is now in collapse. It is suggested that during the end of the warm period (2003–2005), the normal food supply for pollock shifted to less favorable species and that pollock predators, such as arrowtooth flounder, became well established. With the recent shift to a cold period, the favorable food supply for pollock returned to the Bering Sea, but it was less available due to the presence of sea ice. Further, the continued presence of arrowtooth flounder as a predator on pollock remained a negative factor.

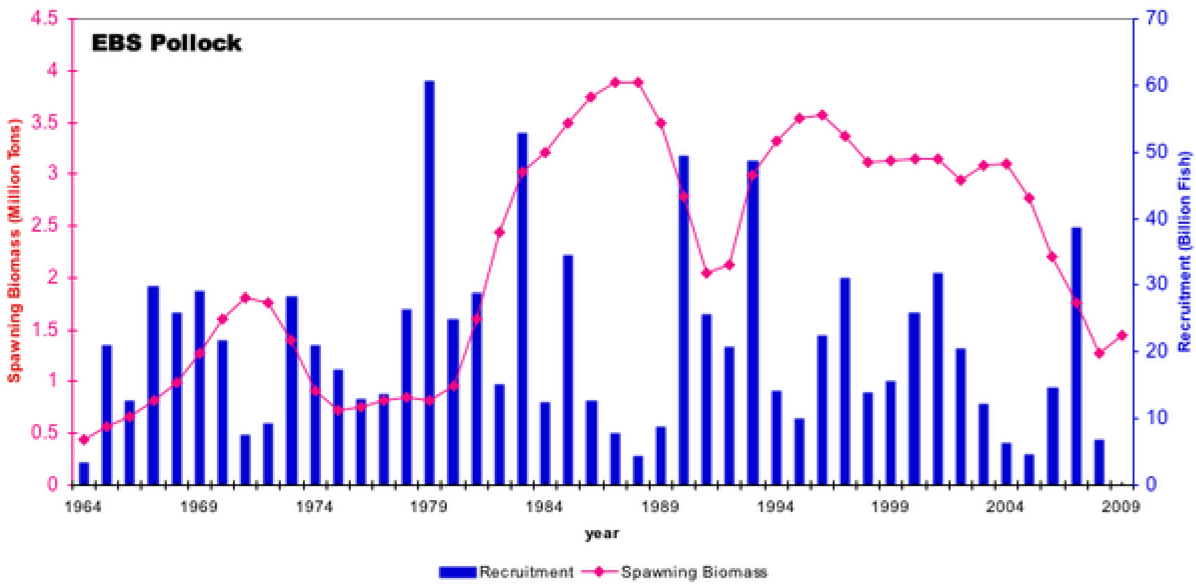

Figure F3. Bering Sea Pollock. Diamonds indicate biomass, and vertical bars indicate recruits to the population each year. From the NOAA/NMFS SAFE report.

Bering Sea temperatures respond both to global warming and large natural variability. While the Bering is cold at present we anticipate a swing back to average temperatures in the coming winter due to El Nino conditions. By 2020 or before, we anticipate a swing back to prolonged warm temperatures. This scenario would continue the negative impact on Arctic and bottom species, such as crab, while favoring sub-Arctic species such as salmon.

Reference

Stock Assessment and Fishery Evaluation Report (SAFE Report) from NOAA / AFSC.

Status of the Barents Sea Ecosystem

Norwegian Institute of Marine Research
http://www.imr.no/filarkiv/havets_ressurser_og_miljo_2009/tilstand_okosyst_BH2sammendrag.pdf/en

September 23, 2009

Summary

The commercial fish stocks in the Barents Sea are, with a few exceptions, in a healthy condition. Positive trends are a growing capelin stock and an increasing spawning stock of Northeast Arctic cod. In a long-term perspective, the water masses are warm, although on average, not as warm as in 2006 (Figure B1). The stock level of blue whiting, a more southern species, has decreased in 2008.

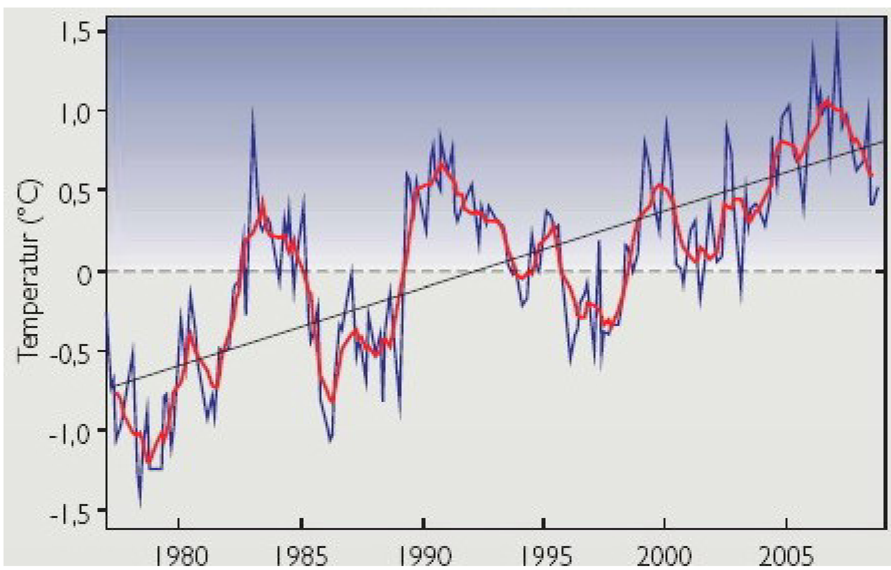

Figure B1. Temperature anomaly in the core of the Atlantic Water flowing into the Barents Sea between Norway and Bear Island (the Fugløya–Bear Island transect). The series are deviations from the long-term mean temperature between 50 and 200 m. Observed values (blue line) and 1 year moving average (red line) are shown. The straight line represents a linear trend over the period.

A clean ocean

Although wind and ocean currents transport various contaminants into the Barents Sea, the level observed in organisms is generally low. The main exception is top predators such as the polar bear, where persistent organic contaminants aggregate.

High temperatures

The water masses in the Barents Sea have been extraordinarily warm since 2000 (Figure B1). However, 2008 was slightly cooler than 2007. This is probably due to a strong reduction of the transport of Atlantic water into the Barents Sea. The amount of ice in the Barents Sea in 2008 was low (Figure B2).

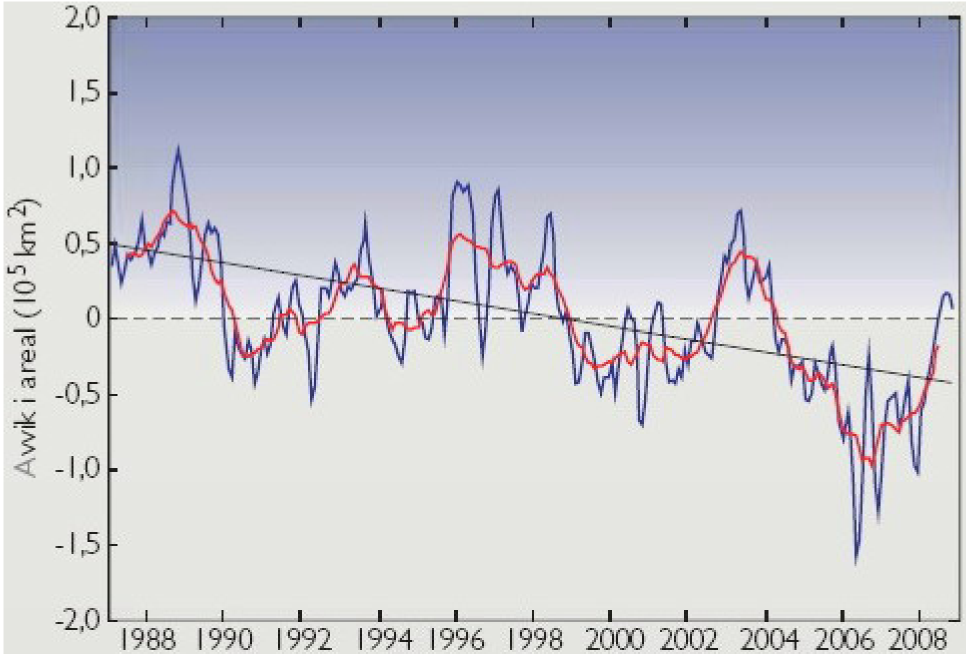

Figure B2. Ice area anomaly for the sector 25–45°E in the Barents Sea, which is the area with the highest variability in ice cover. Monthly mean (blue line) and 1 year moving average (red line) are shown relative to the mean ice area for the period 1987–2007. The straight line represents a linear trend over the period.

Decreasing levels of zooplankton

Compared with the two previous years, considerably less zooplankton was observed in the Barents Sea in 2008. This may be due to a lesser amount of Atlantic water being transported into area, but an increasing capelin stock grazing on zooplankton, mainly copepods and krill, may have contributed to the decrease.

Capelin up, blue whiting down

Based on the number of immature capelin, the stock prognoses indicate an increasing capelin stock the coming year. This is contrary to the prognoses for the other important plankton feeder in the Barents Sea, the young and immature stock (ages 1–4) of Norwegian spring-spawning herring. The year classes 2005–2008 of this stock are smaller than previous years. A decreasing amount of blue whiting is recorded. For polar cod the stock situation seems unchanged.

Healthy stock of Northeast Arctic haddock

The size of the spawning stock of Northeast Arctic cod is slowly increasing and is above the historical average. As in 2007, ICES emphasizes that it is of great importance for the development of this stock that the IUU (illegal, unregulated, unreported) fishery the Barents Sea is stopped. The exact stock size for the Northeast Arctic haddock is difficult to determine. However, the spawning stock is at a relatively high level and strong immature year classes, which will recruit to the spawning stock in the coming years, are observed. The third major demersal fish stock in the Barents Sea, the Greenland halibut, is slowly recovering from a period below historic levels.

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http://www.imr.no/filarkiv/havets_ressurser_og_miljo_2009/1.2_Abiotiske_faktorer_fysikk_sirkulasjon.pdf/en.

The State of Char in the Arctic

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October 15, 2009

Introduction

Arctic Char are the most northerly distributed freshwater fish species and occur in suitable habitats in all Arctic countries. They are widely distributed throughout the circumpolar north (Figure C1) from northernmost areas south to temperate regions (e.g., Switzerland, Italy) (Johnson 1980), with a latitudinal distribution of approximately 40°N to 84°N.

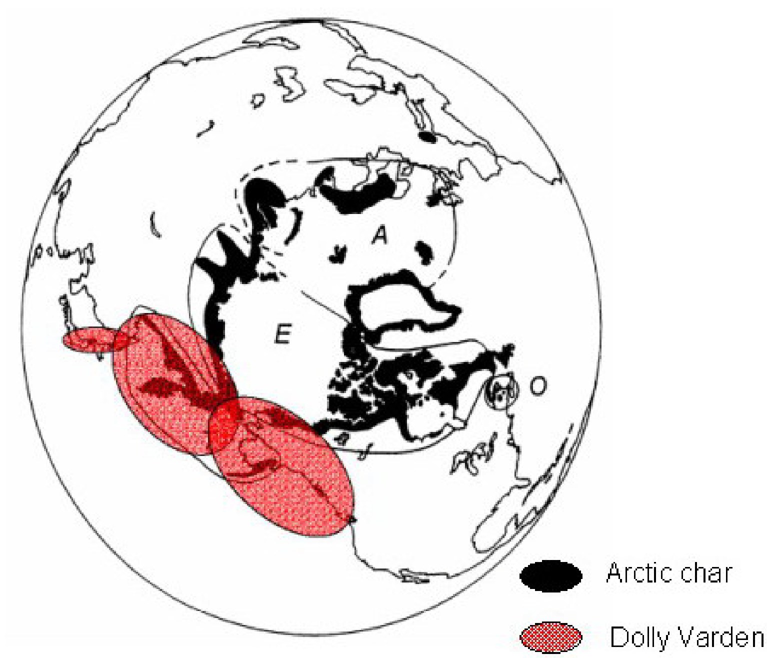

Figure C1. Global distribution of Arctic char and Dolly Varden.

The two most widely distributed groups are Arctic char (*Salvelinus alpinus*), a diverse primarily lake-adapted group (Figure C2), and Dolly Varden (*Salvelinus malma*), primarily a river-adapted group (Figure C3). Both occur as anadromous (sea-run) and freshwater resident forms. They are important components of northern aquatic ecosystems and are economically (subsistence food, commercial and sport fisheries) and culturally significant to northern communities (Conservation of Arctic Flora and Fauna 2001), particularly in Canada. For example, Arctic char made up approximately 45% by number of the top 15 species harvested in Nunavut between 1996 and 2001 (Priest and Usher 2004). The majority of the Canadian commercial Arctic char catch is taken in Nunavut fisheries at Rankin Inlet, Cambridge Bay, Pelly Bay and Nettilling Lake (DFO 2006).

Figure C2. An example of morphological diversity in Arctic char on a regional scale; these fish were sampled from one lacustrine and one marine site in northern Labrador, Canada. Photo by Wendy Michaud.

Figure C3. Adult male anadromous Dolly Varden char in spawning condition captured in the Firth River, Yukon Territory, Canada. Photo by Jim Johnson.

Formal Status Assessments by Conservation Organizations

Several regional and/or national organizations conduct formal status assessments to conserve biodiversity; examples include the International Union for the Conservation of Nature (IUCN http://www.iucn.org/) based in Europe and Natureserve (http://www.natureserve.org/) based in North America. These are supplemented by formal assessment groups in many countries; e.g., in Canada the Committee on the Status of Endangered Wildlife in Canada (COSEWIC, http://www.cosewic.gc.ca/). All conduct assessments of various taxa (species or taxonomic units below species) according to established criteria and based upon the best available information. Summaries are shown in Figure C4 for IUCN assessments.

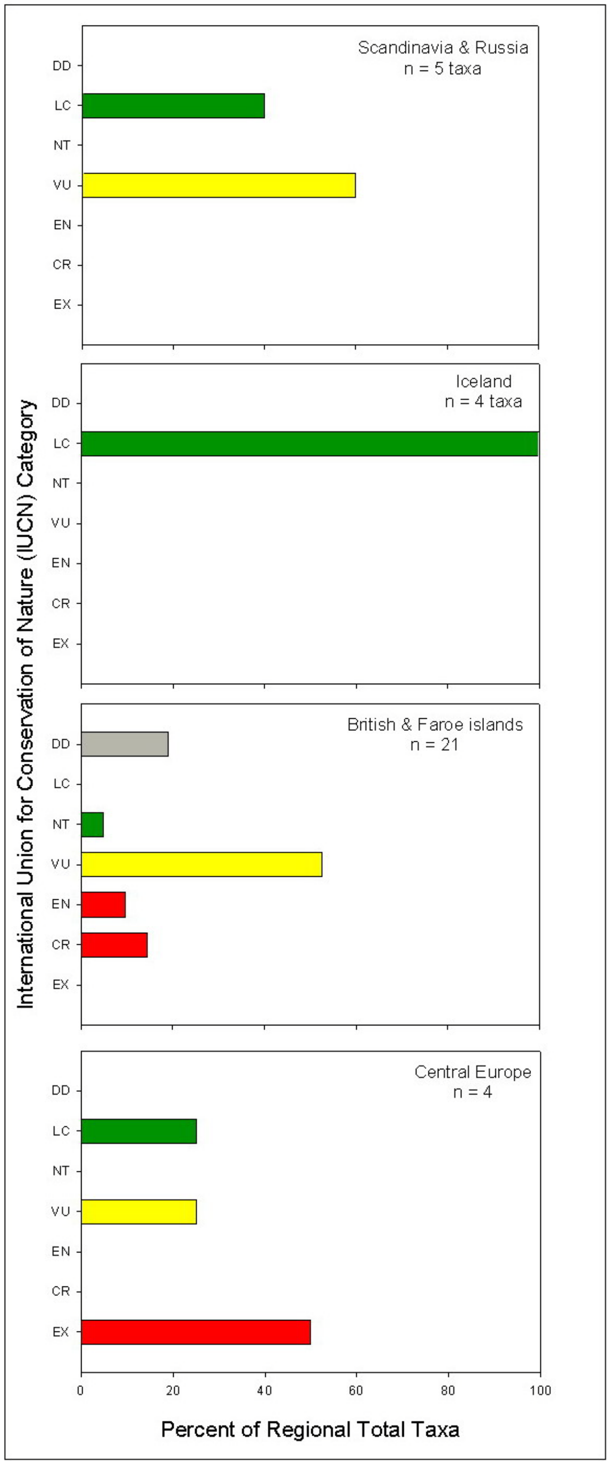

Figure C4. Percentages of European Char Taxa assessed at different levels of risk by IUCN criteria (http://www.iucn.org/; accessed 8 August 2009) for different regions. Note that there is much disagreement regarding the taxonomy used by IUCN, numbers of taxa are small, and assessments tend to be biased towards 'stressed' taxa. Colors indicate different groups of threat levels: gray – information lacking (DD = data deficient), green – assessed at minimal concern (LC = least concern, NT = near threatened), yellow – assessed at increased concern (VU = vulnerable), and, red – assessed at high concern (EN – endangered, CR – critically endangered, EX – extinct). Southern areas exhibit higher percentages of yellow and red threat groups.

Natureserve rankings are not plotted, and taxonomy is not comparable with that used by IUCN (i.e., North American species tend to represent multiple sub-specific taxa). For the five recognized species-level taxa in North America rankings are as follows:

- Southern (non-arctic) – three species are secure and one vulnerable (global rankings);
- Northern (Arctic) – one species is secure.

Natureserve rankings for sub-specific taxa (i.e., components of the above) provide additional understanding as follows:

- Within the continental USA, five of five distinct population groupings of bull char (*S. confluentus*, vulnerable as a species) rank as critically imperiled (n=1) or imperiled (n=4); assessment for 3–4 groups in Canada is underway;
- One southern taxon (*S. alpinus oquassa*) of the Arctic char complex is imperiled in southern Canada and northeastern United States (Natureserve = imperiled, COSEWIC = under assessment; northern Arctic char populations are secure);
- One southern taxon (*S. fontinalis timageamensis*) found in central Ontario of the brook char group is critically imperiled (Natureserve; COSEWIC = endangered);
- The southern taxon (*S. malma lordi*) of the Dolly Varden group is secure throughout its range (southern Alaska, British Columbia to Washington), and the northern taxon (*S. malma malma*) is secure throughout Alaska, however, it appears to be stressed in northwestern Arctic Canada (COSEWIC assessment underway; two of five anadromous populations stressed).

Conclusions

Virtually all stressors which are known to affect fish populations generally have been documented as affecting chars, a group which appears to be particularly susceptible to both local (e.g., exploitation) and pervasive (e.g., climate change) stressors as well as individual and cumulative effects of stressors. From the evidence presented above southern populations (or taxa) of chars, particularly the wider group related to Arctic char, appear to be at greater risk overall as evidenced by higher levels of conservation concern (i.e., more acute conservation status) and by greater percentage of extirpations particularly in Europe. Trends appear to be similar for North America. Two inescapable conclusions thus result: 1) southern populations of chars, particularly those isolated in lakes or requiring unperturbed river habitats, are at acute risk and given their probable evolutionary history represent an irreplaceable component of biodiversity of the Arctic char group; and, 2) southern populations are useful proxies of potential future effects and issues facing northern chars. Accordingly, appropriate care in addressing conservation, management, and stressors of both chars and their ecosystems is required particularly as wide-reaching changes occur throughout the north.

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Additional Resources

Selected Recent Publications on Trends in Canadian Populations of Arctic Char

Dempson, J.B., Shears, M., Furey, G., and Bloom, M. 2004. Review and status of north Labrador Arctic charr, *Salvelinus alpinus*. Canadian Science Advisory Secretariat (CSAS) Research Document 2004/070: 46 p. [available from: http://www.dfo-mpo.gc.ca/Library/284126.pdf; accessed: 24 July 2008].

DFO [Department of Fisheries and Oceans]. 2004a. Cambridge Bay Arctic char. Canadian Science Advisory Secretariat (CSAS) Stock Status Report 2004/10: 15 p. [available from: http://www.dfo-mpo.gc.ca/Library/284796.pdf; accessed: 24 July 2008].

Tallman, R. 2005. Stock assessment report on Kipisa Arctic char. Canadian Science Advisory Secretariat (CSAS) Science Advisory Report 2005/028: 14 p. [available from: http://www.dfo-mpo.gc.ca/csas/Csas/status/2005/SAR-AS2005_028_E.pdf; accessed: 24 July 2008].

Selected Recent Publications on Trends in Canadian Populations of Dolly Varden

DFO [Department of Fisheries and Oceans]. 2001. Rat River Dolly Varden. DFO Science Stock Status Report D5-61: 15 p. [available from: http://www.dfo-mpo.gc.ca/Library/264842.pdf; accessed: 24 July 2008].

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Goose Populations

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March 20, 2008

Since the 1970's, many goose populations have gone through an impressive increase in size. In the last decade, the global goose population almost doubled from 12.5 million birds (Madsen et al. 1996) to a current total of 21.4 million (Wetlands International, 2006). Most of these population increases have coincided with large range extensions within the Arctic, but also into temperate regions. Changing agricultural practices have resulted in new, abundant and high quality food sources for wintering geese (Van Eerden et al. 1996, Fox et al. 2005). This has occurred while hunting pressure has decreased through improved legislative protection, a decline in the ratio of hunters per 1000 geese and the establishment of refuge areas.

Goose populations are intensively monitored. Population estimates are based on simultaneous counts in wintering areas, often supplemented with data on nesting densities, ring recoveries and sightings of colour-marked individuals. Wetlands International (www.wetlands.org) is the organisation which compiles all population data with help of its Goose Specialist Group (www.geese.nl/gsg).

Geese are common in many parts of the Arctic. All Arctic populations are migratory and their annual migration routes and stop over places involve a large proportion of the Northern Hemisphere, including almost all countries in North America, Europe and North, Central and East Asia. Goose populations have a direct and significant influence on Arctic ecosystems as exemplified by recent impacts on tundra vegetation due to expanding populations and via the role played by goslings and eggs as a food source for predators in the Arctic.

The most recent review of water bird populations (Wetlands International, 2006) considers several Arctic goose populations as declining. The declines are widely distributed across all flyways indicating a possible link to phenomena acting on a circumpolar scale. Figure E1 depicts the overall distribution of trends within Arctic goose populations. For nine percent of the population, there is no or insufficient information on trends. Thirty-six percent of the populations are still increasing, thirty-two percent are stable, but twenty-three percent are declining – a proportion slightly higher than compared with ten years ago (Madsen et al. 1996).

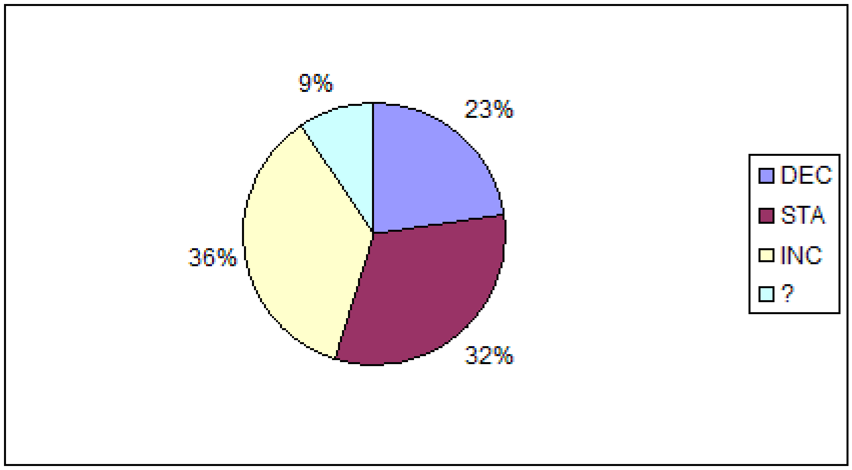

Figure E1. Trends in 47 Arctic Geese populations (Wetlands International, 2006). DEC - population decreasing; STA - population stable; INC - population increasing; ? - unknown

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