# Arctic Report Card 2012

Reviewer 1

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**Sections**

# 1. Atmosphere

## 1.1 - Temperature, Atmospheric Circulation and Clouds

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**Highlights**

- October 2011 through August 2012 was a departure from typical atmospheric conditions of recent years (2003-2010), in that temperature anomalies were small over the central Arctic. Most of the notable weather activity in fall and winter occurred in the sub-Arctic due to a strong positive North Atlantic Oscillation. Summer 2012 was dominated by low sea level pressure.
- Three severe weather events included (1) unusual ~~and deadly~~ cold in late January to early February 2012 across Eurasia, and (2) two record storms characterized by deep central pressure and strong winds near western Alaska in November 2011 and north of Alaska in August 2012.

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**Mean Annual Surface Air Temperature**

In contrast to the years 2003 through 2010, which had substantial positive temperature anomalies in the central Arctic, the period October 2011-August 2012 showed positive temperature anomalies in the sub-Arctic rather than over the central Arctic Ocean (**Fig. 1.1**).

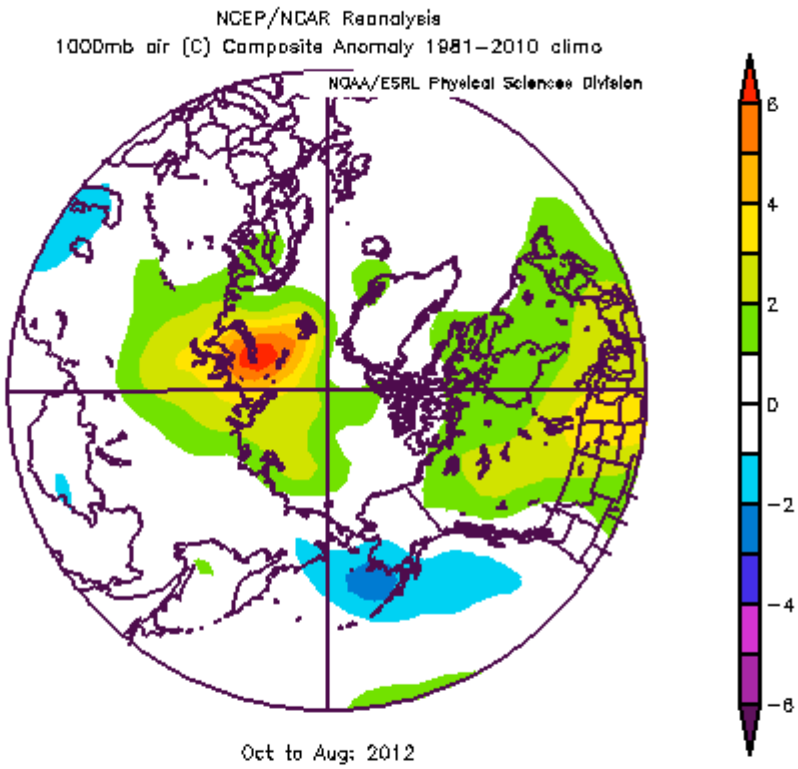



**Fig. 1.1.** Annual average (October 2011 through August 2012) near-surface air temperature anomalies relative to the period 1981-2010. Data are from NOAA/ESRL, Boulder, CO: http://www.esrl.noaa.gov/psd/.

Over a longer time interval, the annual mean surface air temperature over Arctic land areas has experienced an overall warming of about +2ºC since the mid-1960s (**Fig. 1.2**). In 2011, the annual mean air temperature was slightly warmer than in 2009 and 2010. The cooler temperatures in 2009 and 2010 reflected cold continents in winter, while Eurasia had warmer temperatures in spring 2011. The annual mean surface temperature for 2012 is not available, as the year was incomplete at the time of writing.

Positive temperature anomalies were seen everywhere across the central Arctic for the first decade in 21$^{st}$ century (2001-2011) relative to a 1971-2000 baseline period at the end of the 20th Century (**Fig. 1.3**). This temperature pattern is a manifestation of "Arctic Amplification", which is characterized by temperature increases 1.5°C greater than (more than double) the increases at lower latitudes (Overland et al. 2011; Stroeve et al. 2012).

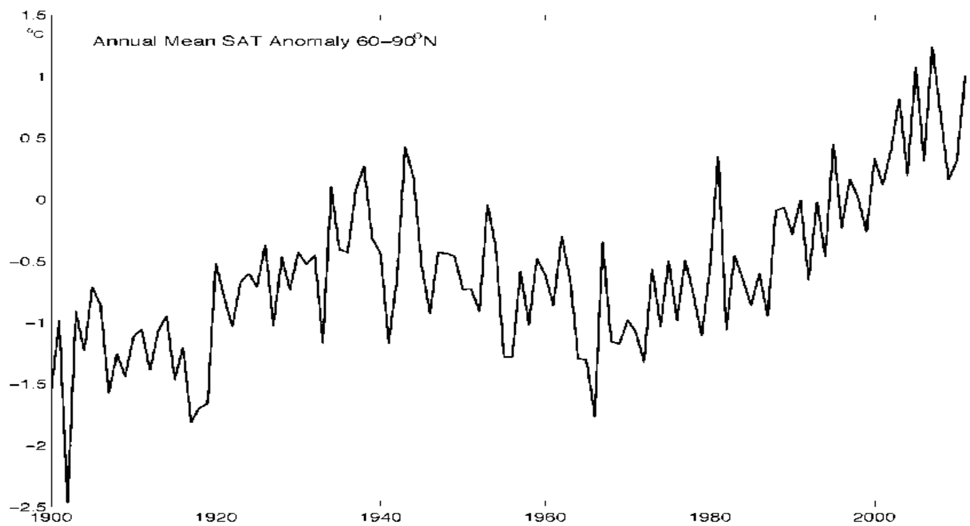



**Fig. 1.2**. Arctic-wide annual average surface air temperature (SAT) anomalies for the period 1900-2011 relative to the 1981–2010 mean value, based on land stations north of 60°N. Data are from the CRUTEM3v dataset at www.cru.uea.ac.uk/cru/data/temperature/. Note: this curve includes neither marine observations nor 2012 data, as the year was incomplete at the time of writing.

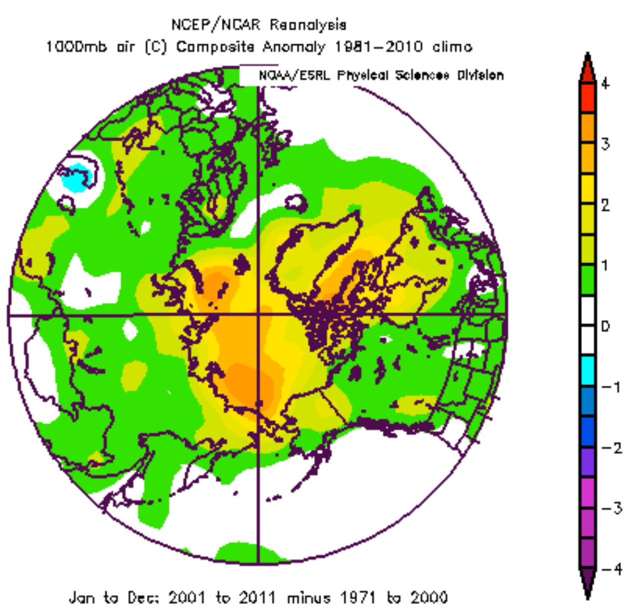



**Fig. 1.3.** Annual average near-surface air temperature anomalies for the first decade of the 21st century (2001–11) relative to the baseline period of 1971-2000. Data are from NOAA/ESRL, Boulder, CO: http://www.esrl.noaa.gov/psd/.

**Seasonal Air Temperatures**

Consistent with the annual average temperatures (**Fig. 1.1**), each seasonal anomaly distribution for near-surface temperatures shows departures primarily in the sub-Arctic (**Fig. 1.4**). Fall 2011 and winter 2012 were characterized by a positive North Atlantic Oscillation (NAO). This promotes the warm temperature anomaly over the Barents and Kara Seas, which are downstream of the stronger winds and lower pressures of the Icelandic low pressure center. This is unlike the Warm Arctic/Cold Continents pattern associated with a negative Arctic Oscillation (AO) climate pattern over the central Arctic (see previous Report Cards), which dominated the previous two falls and winters (2009-10 and 2010-11),

Spring 2012 saw the early formation of the Arctic Dipole (AD) pattern (**Fig. 1.5**) with high pressure on the North American side of the Arctic and low pressure on the Siberian side. In the previous five years this has not occurred until June (Overland et al. 2012). The dipole pattern supported increased winds across the Arctic and warmer temperature anomalies over the East Siberian Sea and western Greenland (**Fig. 1.4c**). In summer 2012 an unusual low pressure, centered on the Pacific Arctic sector, was a new feature of central Arctic weather relative to the last decade (**Fig. 1.6**).

Also noteworthy in **Fig. 1.6** is the high sea level pressure over Greenland, which has been a feature of early summer for the last six years. Higher pressures over Greenland and their influence on Arctic and subarctic wind patterns, a so called blocking pattern, suggests physical connections between it and reduced Arctic sea ice in the summer, loss of Greenland and Canadian Arctic glacier ice, reduced North American snow cover in May and June, and potentially extremes in mid-latitude weather (Overland et al. 2012). See the essays on *Sea Ice*, *Glaciers and Ice Caps*, *Greenland Ice Sheet* and *Snow* for specific information on those topics.

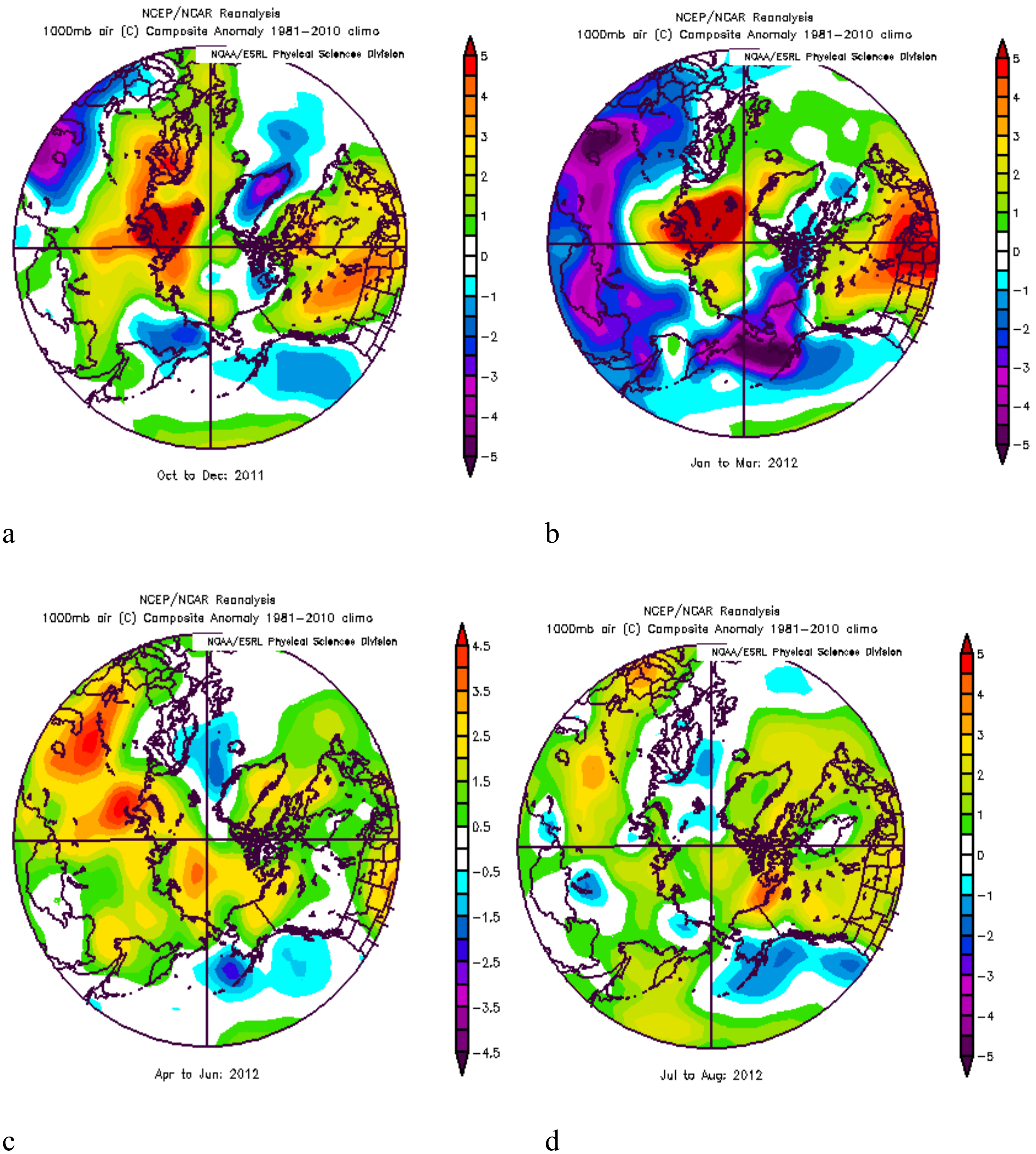



**Fig. 1.4.** Seasonal anomaly patterns for near surface air temperatures in 2012 relative to the baseline period 1981-2010. Fall 2011, (a), winter 2012 (b). spring 2012 (c) and summer 2012 (d). Data are from NOAA/ESRL, Boulder, CO: http://www.esrl.noaa.gov/psd/.

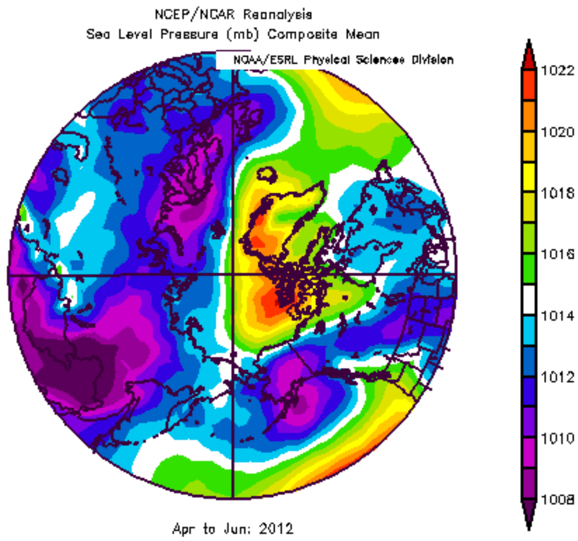



**Fig. 1.5.** Sea level pressure field for April through June 2012 showing the Arctic Dipole (AD) pattern with high pressure on the North American side of the Arctic and low pressure on the Siberian side. Data are from NOAA/ESRL, Boulder, CO: http://www.esrl.noaa.gov/psd/.

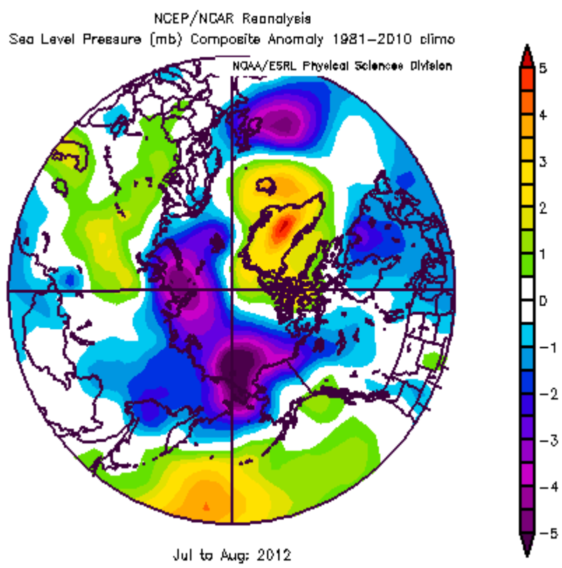



**Fig. 1.6.** In summer 2012 an extensive low sea level pressure anomaly was centered on the Pacific Arctic sector while high pressure remained over Greenland. Data are from NOAA/ESRL, Boulder, CO: http://www.esrl.noaa.gov/psd/.

**Severe Weather**

The period late 2011 through summer 2012 was notable for three severe weather events.

The Bering Sea "superstorm" of November 2011 was one of the most powerful extra-tropical cyclones on record to affect Alaska. Moving northeastward from its origins in the western Pacific Ocean, the storm deepened by 25 hPa in the 24 hours ending November 8, when its central pressure of 945 hPa was comparable to that of a Category 3 hurricane. The storm's forward speed exceeded 60 mph as it approached Alaska and turned northward, passing just offshore of Alaska's western coast, then through the Bering Strait and into the Chukchi Sea. Wind gusts of 40 m/s and 42 m/s were recorded on the western Seward Peninsula and Little Diomede Island, respectively. While there was extensive coastal flooding, fatalities were minimal, in part because the storm was well forecast several days in advance.

In late January-early February 2012, a warm center occurred over the Kara and Laptev Seas and broader, severe cold anomalies occurred over the northern Eurasian sub-Arctic during a brief period of negative AO (see Fig. A4, winter). North America and Eurasia exhibited a sharp contrast in surface temperature anomalies. The United States experienced its fourth warmest winter since national records began in 1895, whereas extremely low temperatures occurred across parts of the Eurasian continent during January 24th-February 14th. This was Europe's worst cold spell in at least 26 years, and >650 people died as a result of the frigid conditions in Russia, Ukraine and Poland. A significant amount of snow fell across the affected areas, resulting in the third largest February snow cover extent (Source: NOAA National Climatic Data Center, State of the Climate: Global Analysis for February 2012, published online March 2012, **http://www.ncdc.noaa.gov/sotc/global/2012/2**). These observations ~~confirm~~ that a negative AO can favor the development of cold weather over Europe and warm weather over North America.

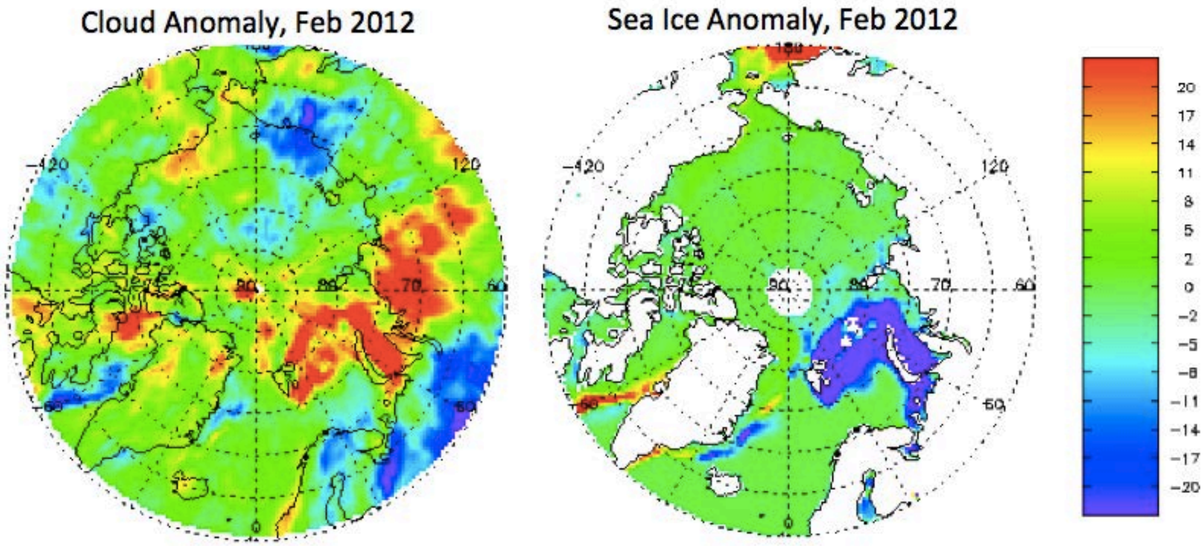
In August 2012, a storm of exceptional intensity affected the Arctic Ocean north of Alaska. The central pressure of 965 hPa made this system one of the strongest August storms to have affected the Arctic Ocean in the past several decades. The storm likely had a significant impact on ocean mixing due to the already reduced sea ice cover, but this remains to be fully evaluated. The storm did have a significant impact on the further retreat of the pack ice, as illustrated in the *Sea Ice* essay (**Fig. 2.5**).

**Cloud Cover**

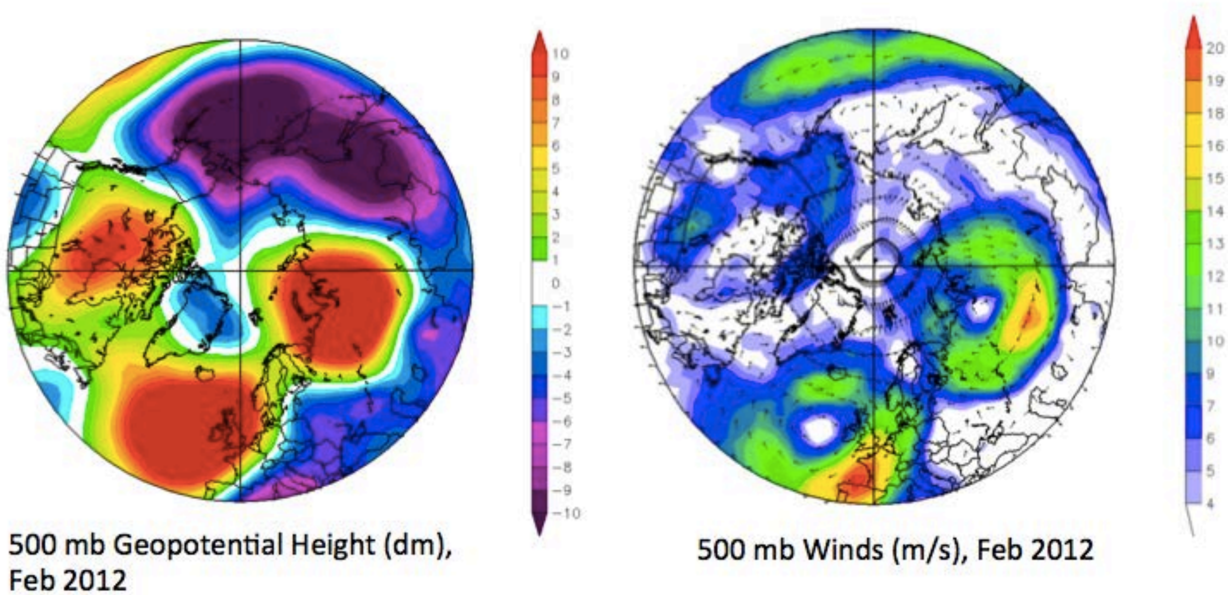
Unlike 2011, when Arctic cloud cover was somewhat higher than normal in winter and lower in the summer, Arctic cloud cover in 2012 was, overall, quite average when compared to the period 2001-2010. However, there were significant monthly anomalies that warrant closer examination, as the spatial patterns varied in important ways on the regional scale.

While clouds influence the surface energy budget, they also respond to changes in the ice cover (Liu et al., 2012). As in recent years, positive cloud cover anomalies (more cloud) over the Arctic Ocean correspond to negative sea ice anomalies (less ice). This was particularly evident in the winter months in the Barents and Kara Seas region, and in the summer months from the East Siberian Sea to the Beaufort Sea. An example for February is shown in **Figs. 1.7a and b**.

Large-scale advection of heat and moisture and the frequency of synoptic scale systems also influence cloud cover (Liu et al., 2007). Positive cloud anomalies over northern Russia and the Kara Sea in the 2011-2012 winter months correspond to southerly flow on the western side of an anticyclonic pattern, while negative cloud anomalies over Siberia are found on the eastern side of the same pattern (**Figs. 1.7 c and d**). Positive cloud anomalies over the Chukchi Sea in June (not shown) also appear to be related more to changes in circulation than to changes in sea ice extent. These patterns are also seen in the surface temperature fields (**Fig. 1.4b, c** respectively). ~~Compared to normal summer cloud conditions, there was increased cloud cover along the track of the severe storm in August 2012 (Nussbaumer and Pinker, 2012),~~




a b




c d

**Fig. 1.7.** Cloud cover (a) and sea ice concentration (b) anomalies (in %) in February 2012 relative to the corresponding monthly means for the period 2002-2010. Data are from the Moderate Resolution Imaging Spectroradiometer (MODIS) on the Aqua satellite. Corresponding 500 mb geopotential height (c) and 500 mb wind field (right) anomalies in February 2012 are from NCEP.

## References

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# 1.2 - Ozone and UV Radiation

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### Highlights

- Temperatures in the Arctic stratosphere in early December 2011 were among the lowest on record. Strong dynamical activity in late December 2011 and January 2012 caused the temperature to rise rapidly and led to conditions unfavorable to sustaining chemical ozone loss.
- Ozone concentrations in the Arctic stratosphere and UV radiation levels at Arctic and sub-Arctic locations during the spring of 2012 were generally within the range of values observed during the first decade of this century.
- Below-average ozone concentrations at several sites in southern Scandinavia led to increases in the UV Index of about 12% during January, February and March of 2012.

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### Introduction

Ozone molecules in the Earth's atmosphere greatly attenuate the part of the Sun's ultraviolet (UV) radiation that is harmful to life. Reductions in the atmospheric ozone amount will always lead to increased UV levels, but other factors such as the height of the Sun above the horizon, cloud cover and aerosols also play important roles. This essay compares ozone and UV radiation measurements performed in the Arctic region in 2012 with historical records.

### Ozone observations

Stratospheric ozone concentrations measured during the spring of 2012 in the Arctic were, by and large, within the typical range observed during the first decade of this century. The 2012 ozone levels were considerably larger than those in the spring of 2011, when unprecedented chemical ozone losses occurred (Manney et al., 2011). The minimum total ozone column[1] for March 2012, averaged over the "equivalent latitude[2]" band 63°-90° N, was 372 Dobson Units (DU[3]). The 2011 record-low was 302 DU (**Fig. 1.8**). The average for 2000-2010 is 359 DU, 13 DU below the value for 2012.

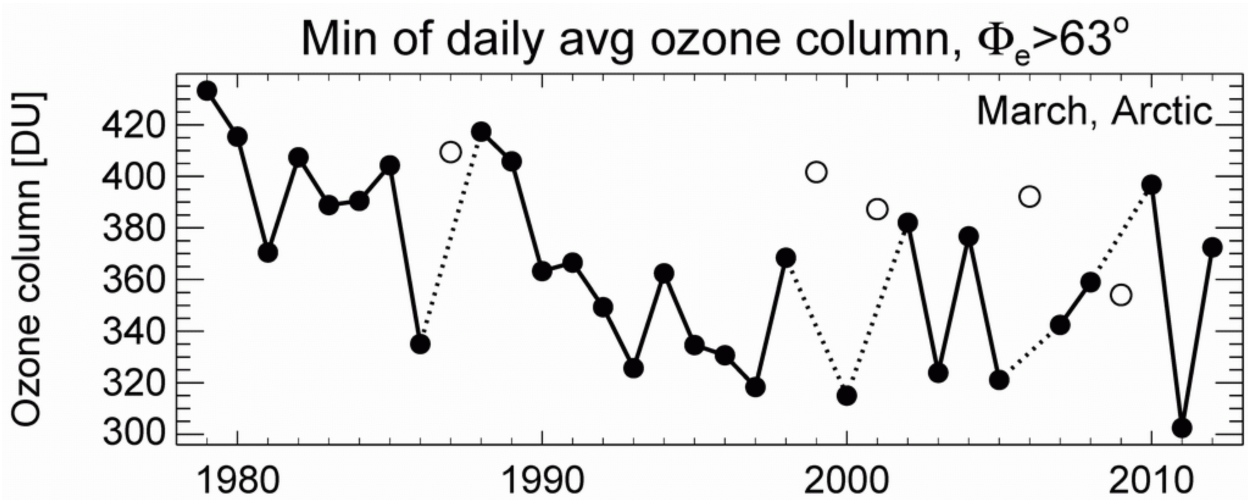


**Fig. 1.8.** Time series of minimum total ozone for March in the Arctic, calculated as the minimum of daily average column ozone poleward of 63° equivalent latitude. Winters in which the vortex broke up before March (1987, 1999, 2001, 2006, and 2009) are shown as circles. Polar ozone in those years was relatively high because of mixing with air from lower latitudes. Figure adapted from Müller et al. (2008), updated using Version 2.8 of the combined total column ozone database produced by Bodeker Scientific, available at http://www.bodekerscientific.com/data/total-column-ozone.

The monthly mean total ozone columns for February through May 2012 are compared with baseline data from the 1978-1988 period in **Fig. 1.9**. During February, total ozone was more than 30% below the baseline value at Svalbard. Regions with monthly mean ozone levels 10% and more below the historical reference encompassed the North Pole, the North Sea, northern Siberia, northern Greenland, Scandinavia, Iceland, the British Isles, Denmark, the Netherlands and northern Germany. Above-average ozone levels were observed over the Aleutian Islands in the north Pacific Ocean. In March, the area with total ozone 10% below the baseline was centered on the North Sea and extended towards southern Scandinavia, the British Isles, France and central Europe. Much of eastern Canada, the eastern United States and southern Alaska was also affected by below-average total ozone columns. In April, Arctic regions with lower-than-normal ozone included the northern part of Canada (Victoria Island) and southern Greenland. Extended areas with large deviations from the historical measurements were not observed in the Arctic during May and through the summer.

The above discussion refers to monthly mean values. Departures from the baseline (either up or down) were larger for individual days. For certain regions and days, the ozone layer was 30% thinner than the long term mean. Deviations exceeding -35% were observed in the southwestern part of Russia as late as the second half of April. Deviations above the reference tended to be smaller in magnitude and less frequent.

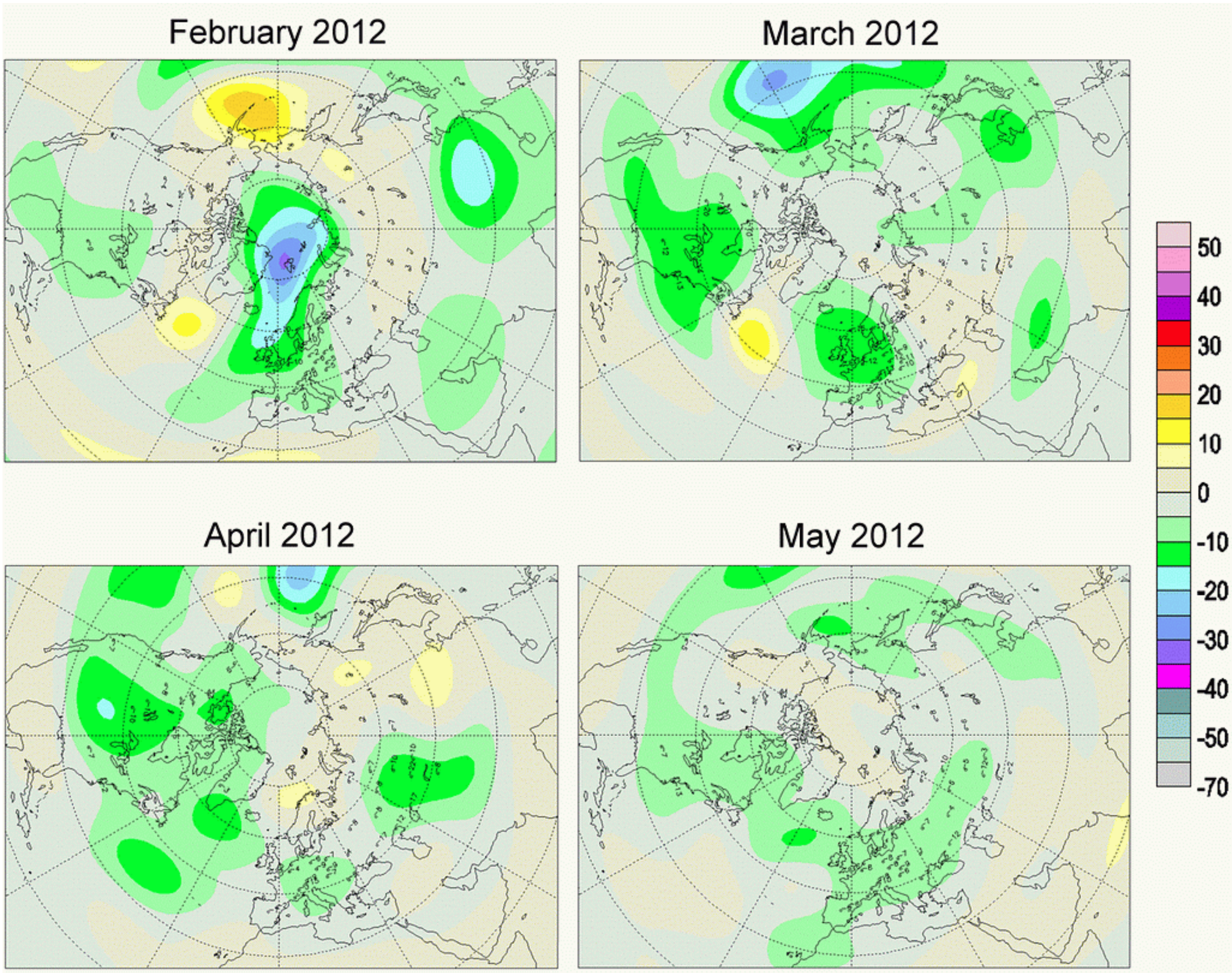


**Fig. 1.9.** Deviation (%) of monthly average total ozone for February, March, April and May 2012 from the 1978-1988 level. Maps were provided by Environment Canada and are available at http://es-ee.tor.ec.gc.ca/cgi-bin/selectMap. The 2012 data are based on ground-based measurements and OMI and GOME-2 satellite data. NOAA Stratosphere Monitoring Ozone Blended Analysis (SMOBA) data were used for the polar night area in February. Reference data for 1978-1988 were estimated using Total Ozone Mapping Spectrometer (TOMS) observations available at http://ozoneaq.gsfc.nasa.gov/nimbus7Ozone.md.

The distribution of total ozone column over the Arctic on 3 April of the years 1981 (a year with a long-lasting and cold Arctic vortex, and relatively low stratospheric chlorine concentrations), 2002 (long-lasting warm vortex, high total chlorine loading), 2011 (long-lasting cold vortex, high chlorine), and 2012 (warm vortex, high chlorine) are illustrated in **Fig. 1.10**. The figure emphasizes that chemical ozone loss resulting from chlorine activation is most effective in years when there is a long-lasting, cold vortex, such as 2011. Years with a warm vortex, such as 2002 and 2012, result in little ozone loss.

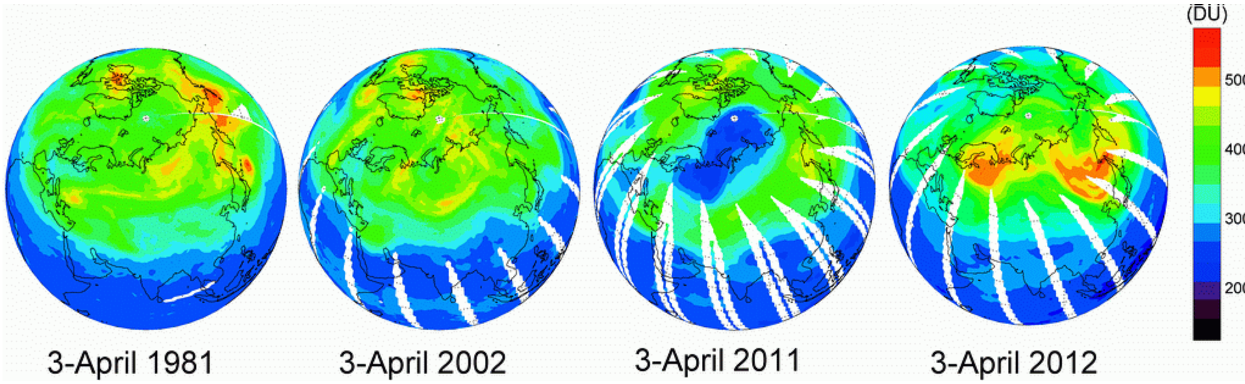


**Fig. 1.10.** Comparison of total ozone column measured by satellites on 3 April 1981, 2002, 2011, and 2012. Data are from the Total Ozone Mapping Spectrometer (TOMS) aboard the Nimbus-7 (1981) and Earth Probe (2002) satellites, and the Ozone Monitoring Instrument (OMI) aboard of the AURA spacecraft (2011 and 2012).

**Chemical ozone loss**

Arctic stratospheric temperatures in December 2011 were among the lowest on record but rose to near average temperatures after strong dynamical activity in late December. Low temperatures facilitate the formation of polar stratospheric clouds (PSC), which provide surfaces for heterogeneous reactions (i.e., reactions between gases and liquid or solid matter) that activate stratospheric chlorine. The activated chlorine, in turn, destroys ozone rapidly in catalytic cycles. Sudden stratospheric warming in January 2012 halted PSC formation and hence the activation of chlorine, and led to conditions that were unfavorable to sustaining chemical ozone loss. The temporal evolution of several parameters that are crucial for stratospheric ozone chemistry are illustrated in the following with data from the Microwave Limb Sounder (MLS) on NASA's Aura satellite (**Fig 1.11**).

Temperatures below the threshold temperature for PSC occurrence and chlorine activation of about 196 K (−77°C) existed locally until late January 2012 (**Fig. 1.11a**). When PSCs are formed, gas-phase nitric acid ($HNO_3$) molecules occurring in the stratosphere are partly converted to cloud. The formation of PSCs at the beginning of the 2011/2012 winter is indicated by the large decrease of gaseous nitric acid in early December 2011 (**Fig. 1.11b**). The conversion of chlorine from inactive "reservoir chemicals" such as hydrogen chloride (HCl) to active forms such as chlorine monoxide (ClO) commenced at about the same time and is indicated by the decrease in HCl (**Fig. 1.11c**) and the increase in ClO (**Fig. 1.11d**). Of note, active chlorine in the form of ClO occurs only in sunlit regions of the vortex. Hence the decrease in HCl appears larger and earlier than the increase in ClO.

ClO is the primary ozone-destroying form of chlorine, so its presence is a sign for the potential for chemical ozone destruction. However, the catalytic cycles that enable ClO to destroy large amounts of ozone also require sunlight. So even with chlorine activated, ozone destruction is typically small in January ~~when much of the Arctic is still dark.~~ The small drop in ozone in late January 2012 indicated in **Fig. 1.11e** suggests that a small amount of ozone was destroyed when the polar vortex was positioned so that substantial portions of it received sunlight.

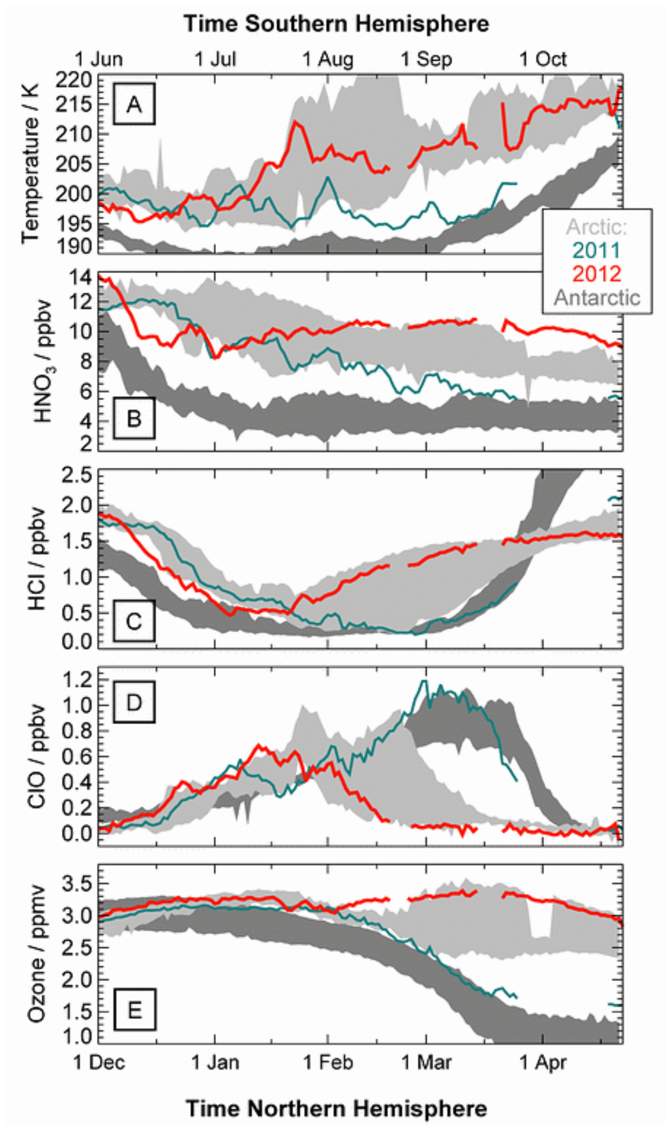


**Fig. 1.11.** Averages of high latitude stratospheric temperatures (panel A), nitric acid ($HNO_3$; panel B), hydrogen chloride (HCl; panel C), chlorine monoxide (ClO; panel D) and ozone (panel E) derived from measurements of the Microwave Limb Sounder (MLS) on NASA's Aura satellite. Measurements of the 2011/2012 Arctic winter (bold red line) are compared with similar data from the 2010/2011 Arctic winter (blue-green lines) during which unprecedented chemical ozone loss had occurred. Light grey shading indicates the range of values observed in Arctic winters between 2004/2005 and 2009/2010. Dark grey shading shows the range of values for Antarctic winters from 2005 through 2011. Temperature and mixing ratios refer to the 485 K potential temperature surface (altitude of approximately 20 km, pressure of about 50 hPa) and were averaged over the polar vortex (the region of strong westerly winds in the stratosphere encircling the pole in winter, within which chemical ozone destruction occurs).

In late January, a very strong and prolonged "stratospheric sudden warming" (SSW) event resulted in temperatures rising above the threshold below which chlorine can be activated, and chlorine was thus converted back to inactive forms by mid-February. No further ozone destruction occurred, and ozone increased slightly through mid-March as vertical motions transported higher ozone down from above.

SSWs are a common dynamical event in the Arctic winter, during which the strong westerly winds that encircle the polar vortex reverse to easterly and polar stratospheric temperatures rise abruptly, sometimes increasing by more than 30 K over 2-3 days. Such events have historically occurred on average about once every two winters, but are irregular, with periods of many years without one occurring (e.g., in most of the 1990s) and other periods such as the past decade having many more than average. The contrast between the meteorological conditions in 2011/2012 with those in 2010/2011 highlights the large range of interannual variability in Arctic winter conditions, and hence in Arctic ozone loss.

**UV Radiation**

UV levels measured at Arctic locations during the first half of 2012 were generally within the typical range of values observed during the last two decades, with notable exceptions discussed below.

**Fig. 1.12** compares measurements of the UV Index for 12 Arctic and sub-Arctic sites performed in 2012 and 2011 with historical measurements. The UV Index is a measure of the ability of UV radiation to cause erythema (sunburn) in human skin. It is calculated by weighting UV spectra with the CIE action spectrum for erythema (McKinlay and Diffey, 1987) and multiplying the result by 40 $m^2/W$. Changes in the UV Index tend to anti-correlate with changes in total ozone. This can be seen by comparing the center panels of **Fig. 1.12**, which show UV Index measurements of 2011 and 2012 relative to the climatological average, with the bottom panels, which show a similar analysis for total ozone. The anti-correlation is most obvious for periods not affected by clouds.

Closer inspection of **Fig. 1.12** reveals that total ozone at the southern Scandinavian sites (last row of **Fig. 1.12**) was significantly below the long-term mean for much of January, February and March 2012, consistent with the ozone maps shown in **Fig. 1.9**. On average, ozone was reduced by 16% over Trondheim, 11% over Finse, 6% over Jokioinen and 10% over Østerås. These reductions led to increases of the UV Index by 11% at Finse and 13% at Østerås. UV levels at Trondheim and Jokioinen were not notably affected, likely because of the dominance of cloud effects. While it is unusual that total ozone remains below the climatological average for three consecutive months, reductions for individual days remained, by and large, within historical limits.

Total ozone at Barrow, Alaska, was 257 DU on 9 June 2012 and 267 DU on 10 June 2012. The long-term mean for the two days is 345 DU and the standard deviation of the year-to-year variability is 23 DU. Thus, total ozone on these two days was 3.8 and 3.4 standard deviations below the climatology. Satellite images (e.g., http://www.temis.nl/protocols/o3field/o3month_omi.php?Year=2012&Month=06&View=np) indicate that the low-ozone event was caused by advection of ozone-poor air from lower latitudes originating from above the United States. The transport of ozone-poor air from lower to higher latitudes is well documented in the literature (e.g., Bojkov and Balis, 2001), but advection from sub-tropical to polar latitudes is less common. As a consequence of low ozone, the UV Index at Barrow on 10 June 2012 was 40% above the mean value for this day.

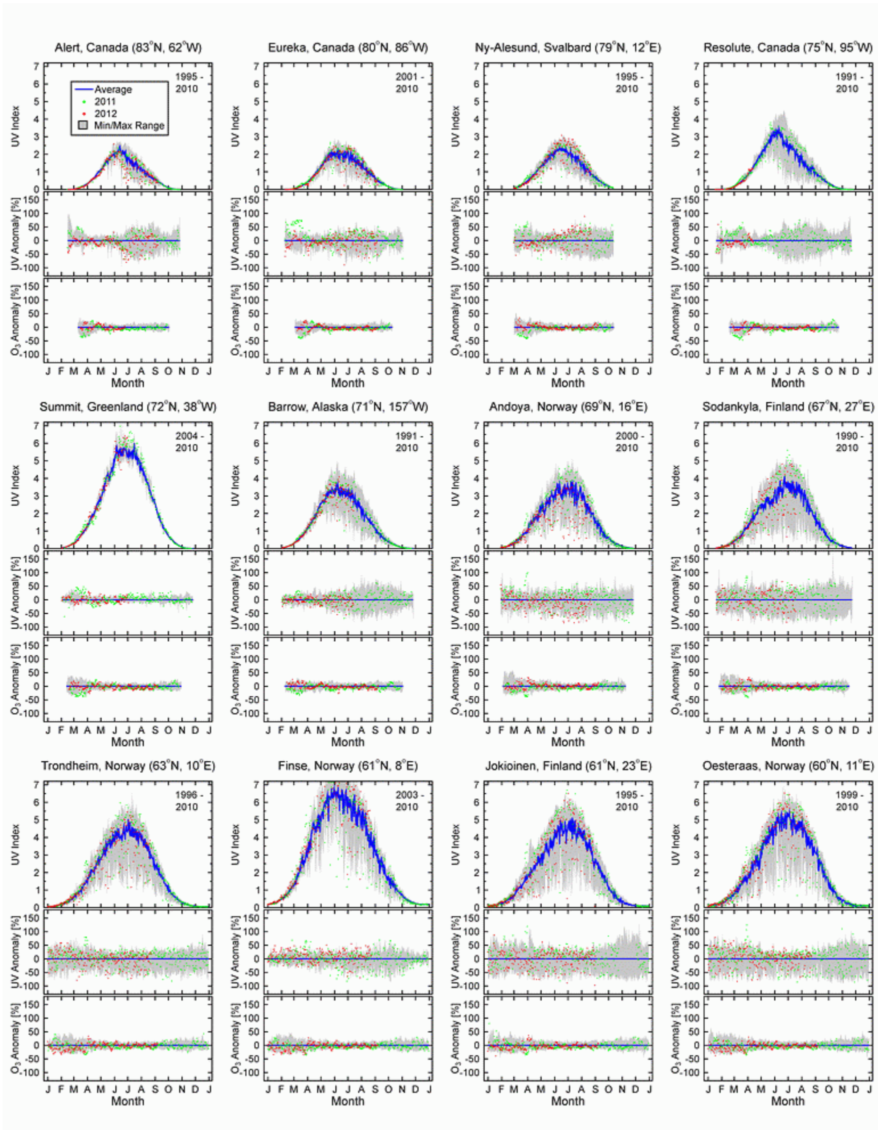


**Fig. 1.12.** Seasonal variation of the UV Index for 12 Arctic and sub-Arctic sites measured by ground-based radiometers. Data are based on the daily maximum UV Index for all sites but Alert, Eureka, and Resolute, which use the UV Index averaged over the period of two hours centered at solar noon. The upper panel for each site compares the climatological average (blue line) with the measurements in 2011 (green dots) and 2012 (red dots), and historical minima and maxima (shaded range). The latter were calculated from measurements during the periods indicated in the top-right corner of the panel. The center panel shows the anomaly in the UV Index, calculated as the percentage departure from the climatological average. The bottom panel shows a similar anomaly analysis for total ozone derived from measurements by the following satellites: TOMS/Nimbus7 (1991-1992), TOMS/Meteor3 (1993-1994), TOMS/EarthProbe (1996-2004) and OMI (2005-2012). The shaded range for the ozone data set is based on data for

1991-2010 (1996-2010 for Trondheim and Finse). Ozone data are available at http://ozoneaq.gsfc.nasa.gov/ and http://avdc.gsfc.nasa.gov/index.php?site=1593048672&id=28. **Fig. 1.12** also highlights measurements made in 2011. The abnormally low stratospheric ozone concentrations in spring of that year (see Arctic Report Card 2011) led to large increases in UV radiation during March and April. These increases were considerably larger than any enhancement observed in 2012.

In addition to atmospheric ozone concentrations, UV radiation is affected by ~~the height of the Sun above the horizon (~~the solar elevation~~)~~, clouds, aerosols (liquid and solid particles suspended in air), the reflectivity of the surface (high, when snow or ice covered), and other factors (Weatherhead et al., 2005). The main driver of the annual cycle is the solar elevation. Sites closest to the North Pole (Alert, Eureka and Ny-Alesund in **Fig. 1.12**) have the smallest peak radiation with UV Index remaining below 4 all year. Although UV Indices below 5 are considered "low" or "moderate" (WHO, 2002), people involved in certain outdoor activities may receive higher-than-expected UV doses if their faces and eyes are oriented perpendicular to the low Sun or if they are exposed to UV radiation reflected off snow.

Clouds lead to a large variability in UV levels on time scales from minutes to days, but their effect is largely reduced when the ground is covered by fresh snow (Bernhard et al. 2008). Measurements at Barrow, and to a lesser extent at Alert and Eureka, show a large asymmetry between spring (low variability) and fall (high variability) because the surface at these sites is covered by snow until about June and free of snow thereafter until the beginning of winter. During summer and fall, the variability introduced by clouds is substantially larger than that related to ozone variations (compare shaded ranges in center and bottom panels of **Fig. 1.12**).

**Footnotes**

[1]Total ozone column is the height of a hypothetical layer that would result if all ozone molecules in a vertical column above the Earth's surface were brought to standard pressure (1013.25 hPa) and temperature (273.15 K).

[2]Equivalent latitude is a latitude-like coordinate aligned with the polar vortex (Butchart and Remsberg, 1986).

[3]Dobson Unit, the standard unit for measuring the total ozone column. 1 DU equals a column height of 0.01 mm and corresponds to $2.69 \times 10^{16}$ molecules / $cm^2$.

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# Arctic Report Card 2012

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**Sections**

# 2. Sea Ice and Ocean

## 2.1 - Sea Ice

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**Highlights**

- Record minimum Arctic sea ice extent occurred in September 2012; The lowest observed during the satellite record (1979-present) and 49% below the 1979-2000 average minimum.
- 2012 had the largest loss of ice between the March maximum and September minimum extents during the satellite record, and the extent of multi-year ice continued to decrease.
- A severe storm in August accelerated ice loss in the Pacific Arctic.

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**Sea ice extent**

Sea ice extent is used to describe the state of the Arctic sea ice cover. There is an accurate record of extent since 1979, determined from satellite-based passive microwave instruments. There are two months each year that are of particular interest: September, at the end of summer, when the ice reaches its annual minimum extent, and March, at the end of winter, when the ice is at its maximum extent. Ice extent in March 2012 and September 2012 are illustrated in **Fig. 2.1**.

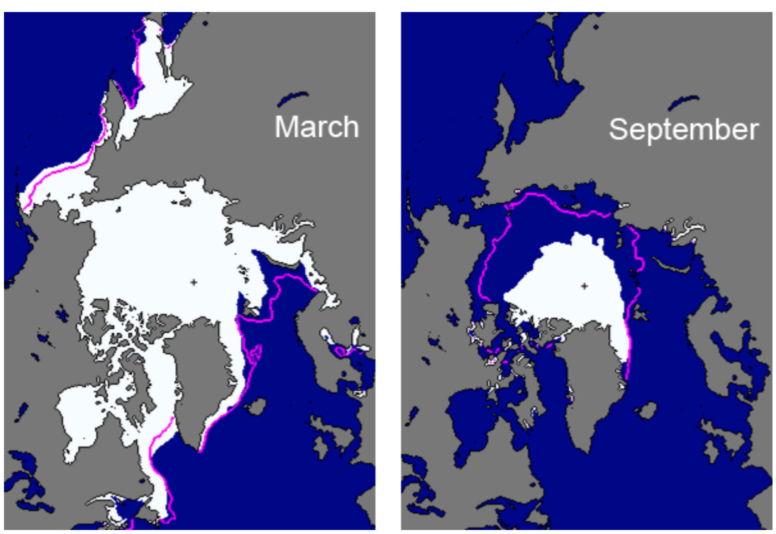

**Fig. 2.1.** Sea ice extent in March 2012 (left) and September 2012 (right), illustrating the respective monthly averages during the winter maximum and summer minimum extents. The magenta line indicates the median maximum and minimum ice extents in March and September, respectively, during the period 1979-2000. Maps are from the National Snow and Ice Data Center Sea Ice Index: nsidc.org/data/seaice_index.

Based on estimates produced by the National Snow and Ice Data Center, on September 16, 2012 the sea ice cover reached its minimum extent for the year of 3.41 million $km^2$. This was the lowest in the satellite record; 18% lower than in 2007, when the previous record of 4.17 million $km^2$ was recorded (**Fig. 2.2**). Overall, this year's minimum was 3.29 million $km^2$ (49%) below the 1979-2000 average minimum of 6.71 million $km^2$. The last six years, 2007-2012, have the six lowest minimum extents since satellite observations began in 1979.

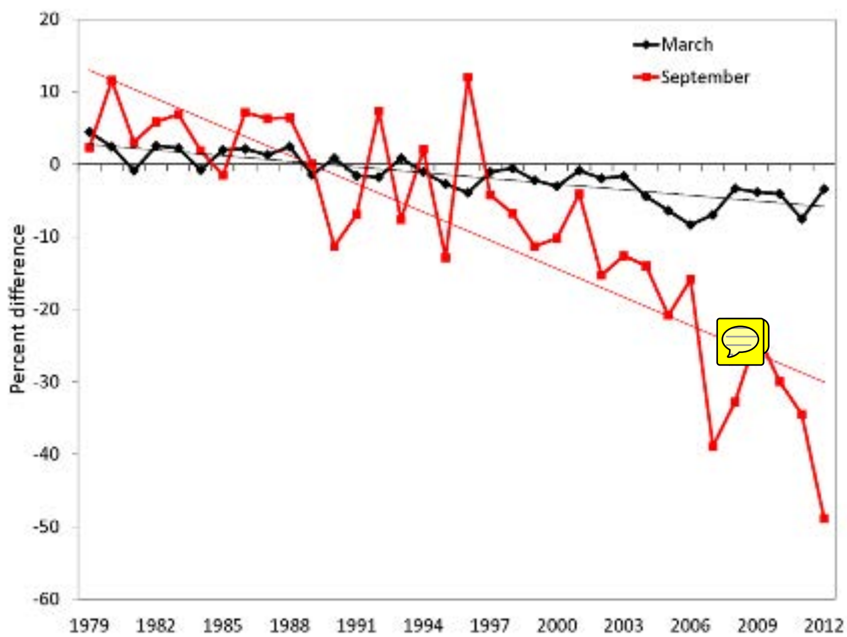


**Fig. 2.2.** Time series of ice extent anomalies in March (the month of ice extent maximum) and September (the month of ice extent minimum). The anomaly value for each year is the difference (in %) in ice extent relative to the mean values for the period 1979-2000. The thin black and red lines are least squares linear regression lines with slopes indicating ice losses of -2.6% and -13.0% per decade in March and September, respectively.

In March 2012 ice extent reached a maximum value of 15.24 million $km^2$ (**Fig. 2.2**), 4% below the 1979-2000 average. This was the highest maximum in 9 years, but 2004-2012 has the nine lowest maximum extents since 1979. The relatively high maximum extent in March 2012 was due to conditions in the Bering Sea, where ice extent was at or near record levels throughout the winter and spring.

After reaching maximum extent, the seasonal decline began slowly, particularly in the Bering Sea, and around mid-April, extent was close to the 1979-2000 average for the time of year. However, soon after that the decline accelerated and was faster than normal through much of the summer. August 2012 was a period of particularly rapid ice loss, in part due to a storm that passed through the region at the beginning of the month (see below). Overall, 11.83 million km$^2$ of ice was lost between the maximum and minimum extents. This is the largest seasonal decline in the record and 1 million km$^2$ more than in any previous yea

Sea ice extent has decreasing trends in all months and virtually all regions (the exception being the Bering Sea during winter). The September monthly average trend is now -91,600 km$^2$ per year, or -13.0 % per decade relative to the 1979-2000 average (**Fig. 2.2**). The magnitude of the trend has increased every year since 2001. Trends are smaller during March, but still decreasing and statistically significant. The March trend is -2.6% per decade (**Fig. 2.2**).

Average ice extents for each month are presented in **Fig. 2.3**. Three time periods are compared; the reference period 1979–2000, 2001 to 2006, and the last six years (2007–2012) beginning with the previous record minimum of 2007. The 1979–2000 period has the largest ice extent for every month, with the greatest difference between the time periods occurring in September. Comparing the two 21$^{st}$ Century periods shows that ice extent is similar in winter and spring, but summer values are significantly lower in 2007–2012.

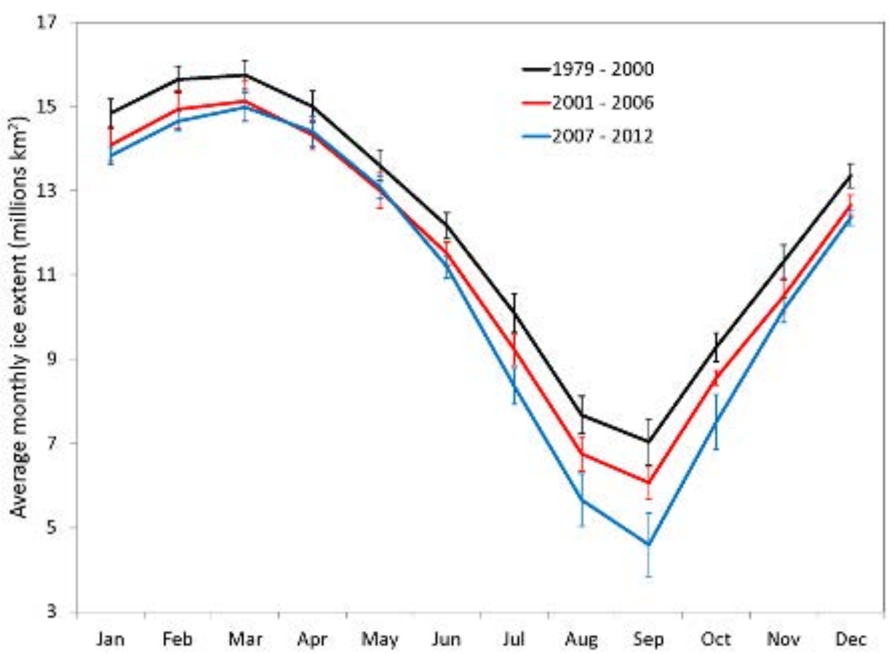


**Fig. 2.3.** Mean monthly sea ice extent for the reference period 1979-2000 (thick black line) and for the 2001-2006 (red line) and 2007–2012 (blue line). The vertical bars represent one standard deviation about the mean value for each month.

## Spatial distribution of sea ice

In 2007 persistent winds through the summer, created by an Arctic dipole circulation pattern (see Fig. A3 in Arctic Report Card 2007), resulted in a compact ice cover and an ice edge far to the north on the Pacific side of the Arctic. However, the circulation also pushed ice onto the coast in the Laptev Sea, completely blocking the Northern Sea Route. In the years since 2007, the pattern of ice loss has varied, but a tongue of older ice in the East Siberian Sea has persisted through the summer. This tongue was particularly evident in 2010 and 2011. In 2012 that tongue of ice mostly melted away, aided by the August storm, and ice retreated significantly around the entire perimeter of the ice pack (**Fig. 2.1**, right panel). This includes the Atlantic side, north of Svalbard, where extents had been near normal in recent years. Overall, compared to 2007 there was more ice this year in the central Arctic north of the Bering Strait, but less ice nearly everywhere else.

## Age of the ice

~~The age of the ice is another key descriptor of the state of the sea ice cover.~~ Older ice tends to be thicker and thus more resilient to changes in atmospheric and oceanic forcing than younger ice. The age of the ice is determined using satellite observations and drifting buoy records to track ice parcels over several years. This method has been used to provide a record of ice age since the early 1980s (**Fig. 2.4**). The distribution of ice of different ages illustrates the extensive loss in recent years of the older ice types (Maslanik et al., 2011). Analysis of the time series of areal coverage by age category indicates the continued recent loss of the oldest ice types, which accelerated starting in 2005 (Maslanik et al., 2011). For the month of March, older ice (4 years and older) has decreased from 26% of the ice cover in 1988 to 19% in 2005 and to 7% in 2012. This represents a loss of 1.71 million km$^2$ since 2005. In March 1988, 58% of the ice pack was composed of first-year ice (ice that has not survived a melt season). In March 2012, first-year ice dominated the pack (75%). Younger ice is typically thinner than older ice (e.g., Maslanik et al., 2007), so the current ice pack is likely thinner on average than it was in 1988. Note that, from March 2011 to March 2012, much of the three-year-old ice north of the Canadian Archipelago survived the melt season, resulting in an increase in four-year-old ice in March 2012 (5%, compared to 2% in March 2011). This increase was directly associated with a reduction in the fraction of three-year-old ice, which decreased from 9 to 7%.

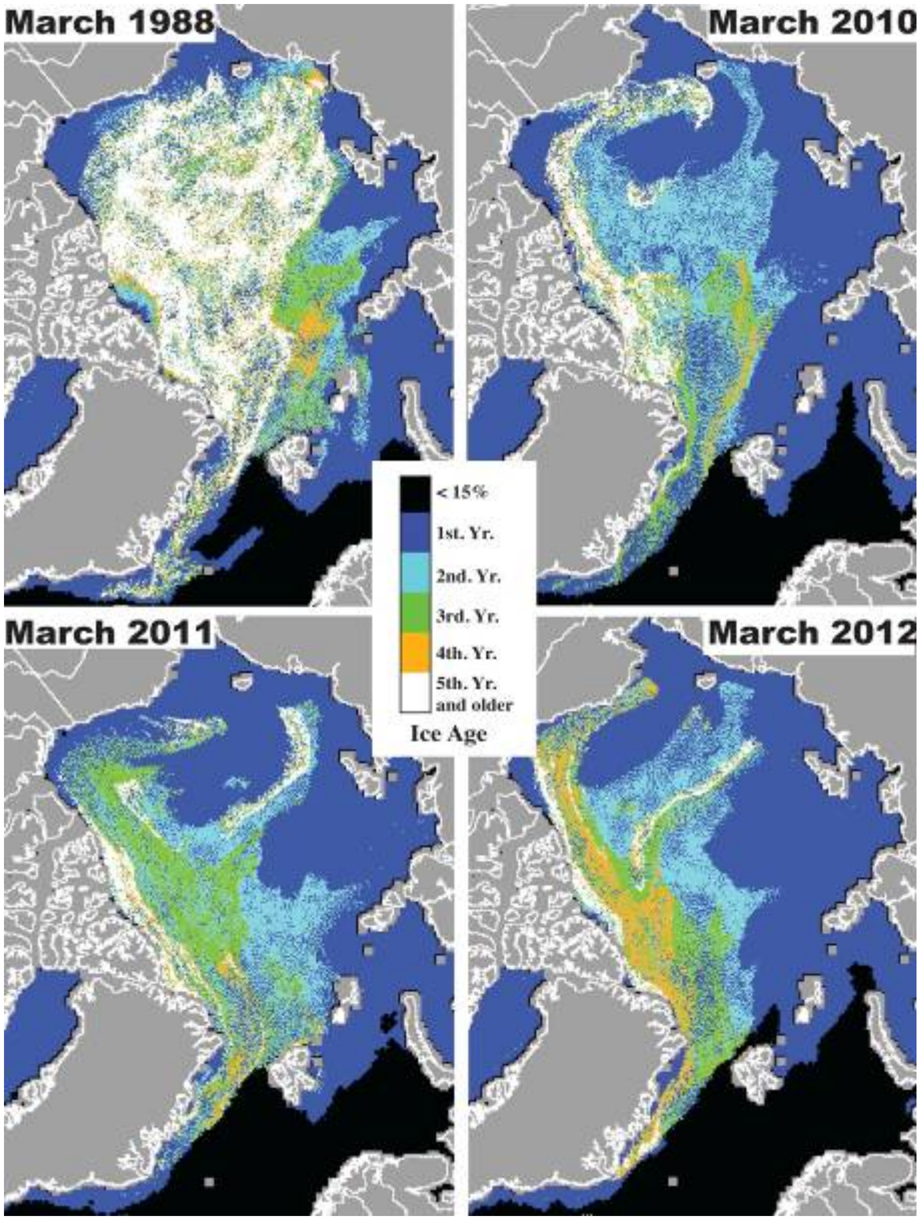


**Fig. 2.4.** Sea ice age in the first week of March 1988, 2010, 2011 and 2012, determined using satellite observations and drifting buoy records to track the movement of ice floes. Figure courtesy of J. Maslanik and M. Tschudi.

**Impact of an August Storm**

A ~~severe~~ storm in the Chukchi and East Siberian seas in early August 2012 (**Fig. 2.5**) accelerated ice loss and helped to quickly remove ice from the region (also see the essay on *Air Temperature, Atmospheric Circulation and Clouds*). As **Fig. 2.4** indicates, most of this region was covered by first year ice. The storm blew the ice southward into warmer water, where satellite observations indicated that it melted in a few weeks (**Fig. 2.5**). As the ice melted and diverged, ice concentration quickly fell below the detection limit of passive microwave sensors, though small amounts of ice were observed for a couple of weeks afterwards by operational ice analysts using other imagery.

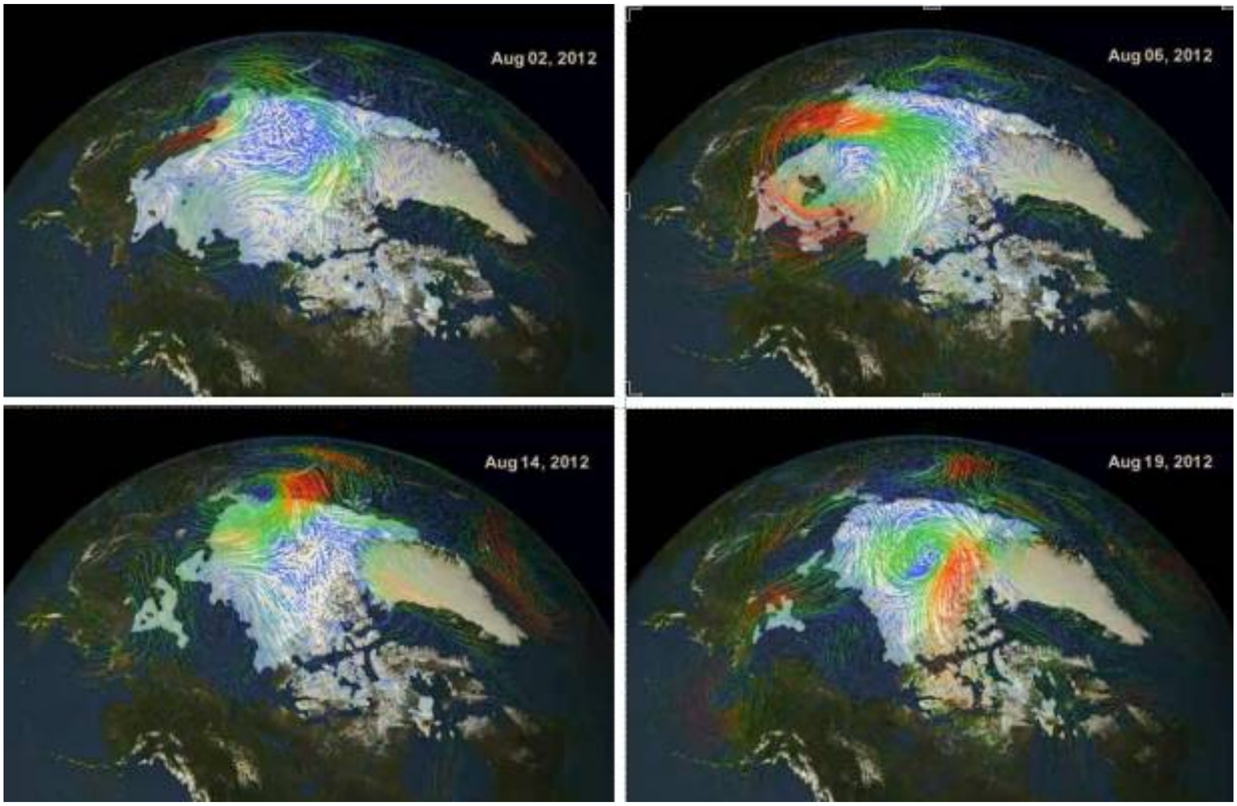


**Fig. 2.5.** Storm-induced breakup and melt of sea ice in the Western Arctic. The sequence illustrates breakup of ice and movement of ice southward into warmer water.

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## 2.2 - Ocean

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### Highlights

- The 2011 annual wind-driven circulation regime was anticyclonic, supporting continued high volumes of freshwater in the Beaufort Gyre region and consistent with a 2012 shift of the Beaufort Gyre freshwater center to the west.
- Sea surface temperatures in summer continue to be anomalously warm at the ice-free margins, while upper ocean temperature and salinity show significant interannual variability with no clear trends.
- Oceanic fluxes of volume and heat through the Bering Strait increased by ~ 50% between 2001 and 2011.
- Sea level exhibits decadal variability with a reduced correlation to sea level atmospheric pressure since the late 1990s.

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### Wind-driven circulation

In 2011, the annual wind-driven ice and surface ocean circulation was anticyclonic (**Fig. 2.6**) with a well-organized clockwise Beaufort Gyre (BG) over the entire Canada Basin. To examine this in context with the most recent wind-driven circulation, we compare the average circulation pattern for September 2011–August 2012 to the average over the preceding 12 months (**Fig. 2.7**). The overall sense of the ice and surface ocean circulation during September 2010–August 2011 was similar to the 2011 average (**Fig. 2.6**). Sea ice and surface freshwater transport through Fram Strait originated from the Laptev Sea and in a strong eastward current off northern Greenland. Surface waters from the Laptev Sea were also partly swept into the enlarged BG but flow was directed primarily towards

Fram Strait. Near-surface waters and sea ice from the Chukchi and East Siberian Seas were driven westwards by winds (**Figs. 2.6 and 2.7** [left panel]). By contrast, the wind-driven anticyclonic BG circulation between September 2011 and August 2012 was weaker than the average over the preceding 12 months. In 2011-2012, the somewhat weaker wind stress curl over the BG does not appear to have affected freshwater accumulation by Ekman transport (see **Fig. 2.11** and discussion). However, the circulation patterns are consistent with the slight shift of the BG freshwater center to the west in 2011-2012. That same year, cyclonic circulation was intensified over the Norwegian, Barents and Kara seas, and partially over the Laptev Sea. This drove intensified sea ice and surface water flow from the Kara and Laptev seas northward and then out of the Arctic Ocean via Fram Strait. This wind driving forced earlier ice-free conditions in these regions, and therefore increased solar absorption into the upper ocean (see **Fig. 2.9** and discussion). In the Beaufort and Chukchi seas, unusually strong westward winds resulted in delayed ice loss from the Chukchi Sea and accumulation of sea ice in the vicinity of Wrangel Island, where some ice persisted through the end of summer (see the *Sea Ice* essay for more information on ice conditions in 2012). Surface-ocean temperatures in August were subsequently relatively cool in these regions (see **Fig. 2.9** and discussion).

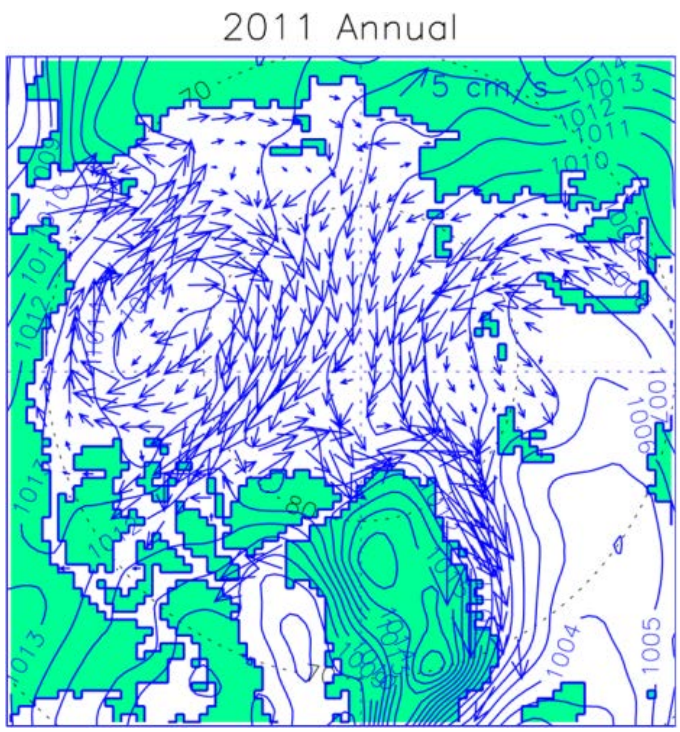


**Fig. 2.6.** Annual simulated wind-driven ice motion (arrows) and observed sea level atmospheric pressure (hPa, solid lines) for 2011. Results are from a 2D coupled ice-ocean model (Proshutinsky and Johnson 1997, 2011) forced by wind stresses derived from NCEP/NCAR reanalysis 6-hourly sea level pressure fields.

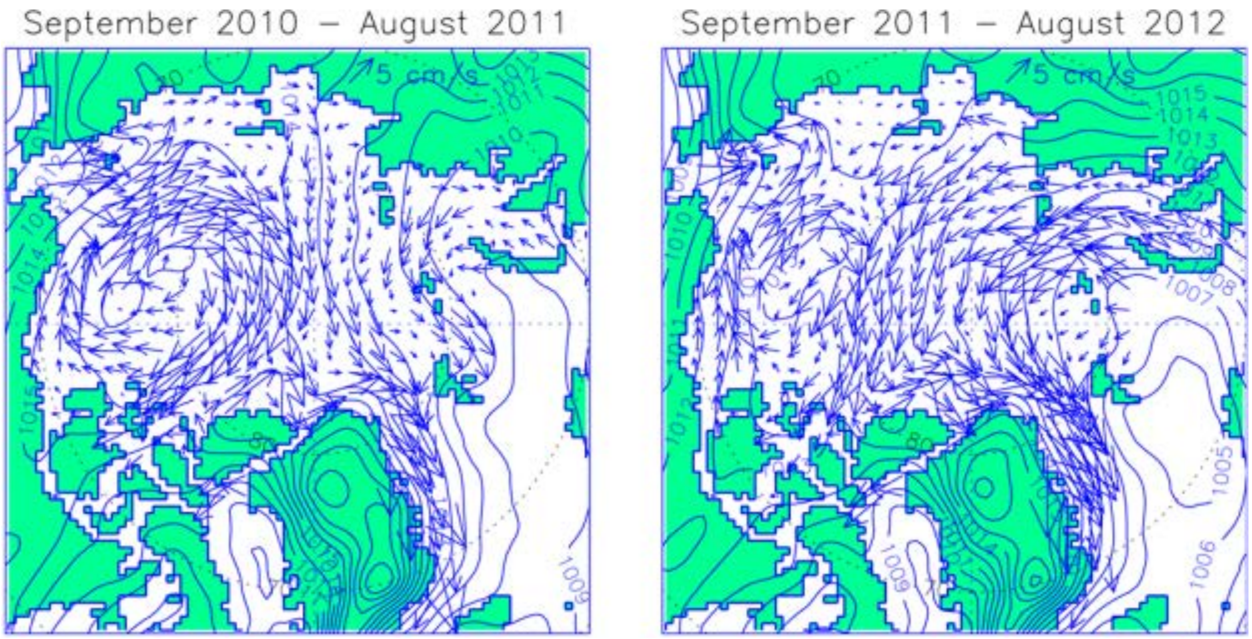


**Fig. 2.7.** As in Fig. 2.6, but panels indicate the mean wind-driven ice motion for September to August (left: 2010-2011, right: 2011-2012).

Ice drift patterns in summer are critical to summer sea ice conditions and upper-ocean properties, and influence ice conditions over the following seasons. When strong anticyclonic ice drift prevails in the summer (as in 2007), significant volumes of sea ice can be pushed out of the Arctic Ocean leaving vast areas of open water which can accumulate heat from direct solar radiation and delay autumn freeze up. By contrast, under cyclonic atmospheric forcing (as in 2009), sea ice outflow via Fram Strait can be reduced (**Fig. 2.8**). In these summers with more sea ice, less heat is accumulated in the upper ocean, allowing earlier autumn freeze-up. While the average wind-driven circulation in August over the years 1948 to 2012 is cyclonic (not shown), the August mean wind-driven ice and surface-ocean circulation since 2007 shows significant interannual variability (**Fig. 2.8**). Cyclonic circulation persisted in August 2008, 2009 and 2012, although with weaker Fram Strait outflows in 2008 and 2009.

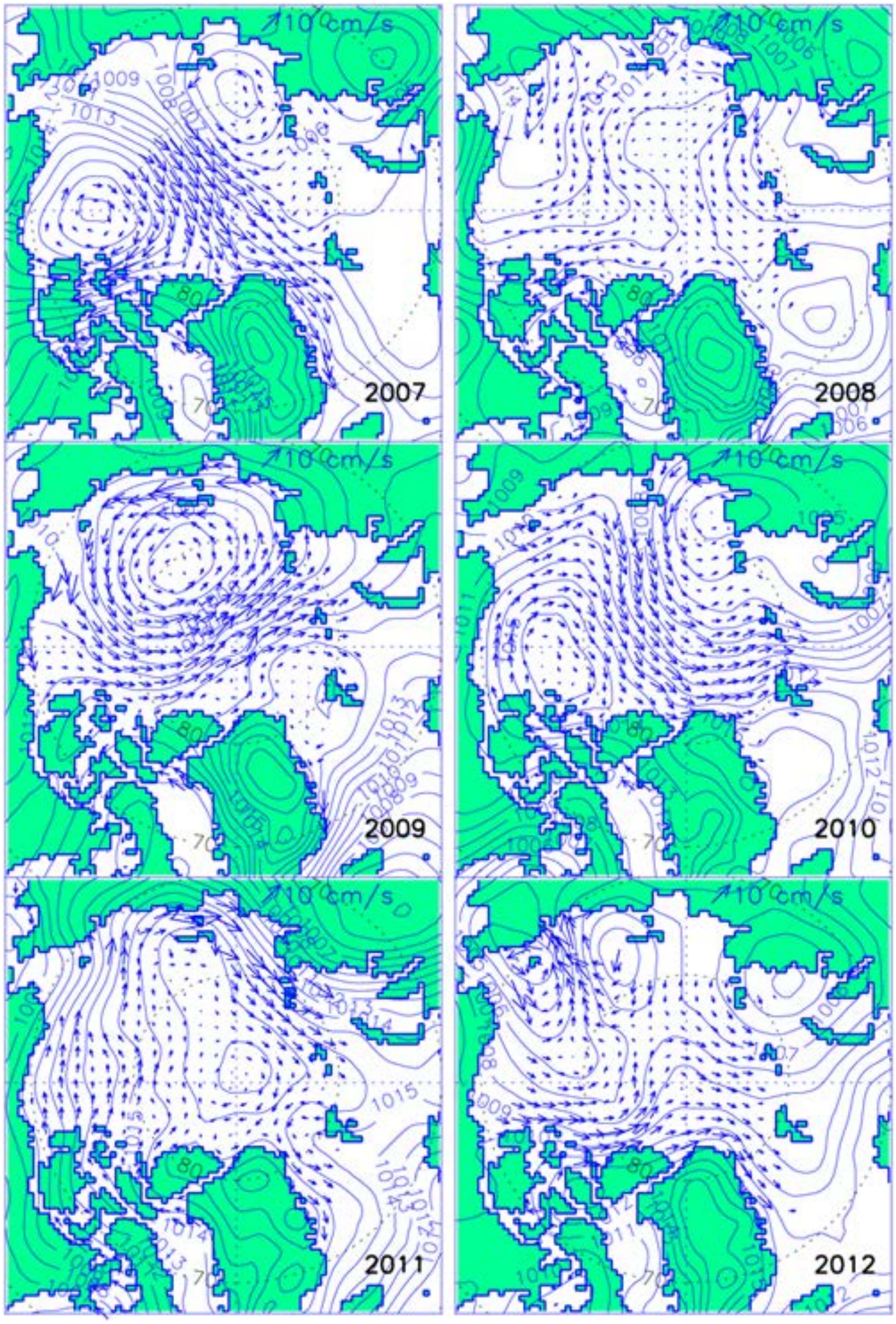


**Fig. 2.8.** As in Fig. 2.6, but panels show the monthly mean wind-driven ice motion for August of the years indicated in the bottom right of each panel. Sea-ice concentrations (NOAA_OI_SST_V2 data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at http://www.esrl.noaa.gov/psd/) are for August 15 of each year; only concentrations greater than 30% are shown here.

## Ocean Temperature and Salinity

**Upper-ocean temperature.** Mean sea surface temperature (SST) anomalies in August 2012, relative to the August mean of 1982-2006, were more than $2^{0}$C higher in parts of the Beaufort, Laptev and Kara seas (**Fig. 2.9**). This excess heat, derived from solar radiation, can be stored below a strong summer halocline as a Near Surface Temperature Maximum (NSTM). Jackson et al. (2012) analyzed upper-ocean properties in the Canadian Basin through 2010 to demonstrate that the NSTM loses heat to the surface layer throughout winter, contributing to the surface-ocean heat budget year round.

While most Arctic boundary regions displayed anomalously warm SST in 2012, a strong cold anomaly was evident in the Chukchi Sea. This appears to be related to the unusual sea ice extent pattern, and in particular the persistence of sea ice in this area even as the main ice pack retreated northward (see the *Sea Ice* essay for more information on ice conditions in 2012). Further, a storm during the first week of August (see the essay on *Air Temperature, Atmospheric Circulation and Clouds*) caused rapid degradation of this southern ice patch (see **Fig. 2.5** in the *Sea Ice* essay) and produced very cool SSTs, which persisted for at least a week. Preliminary analysis of in situ UpTempO buoy data from this area (http://psc.apl.washington.edu/UpTempO) indicates that SST returned to warmer values with further ice loss and solar absorption, and possibly some contribution from sub-surface heat mixed upward.

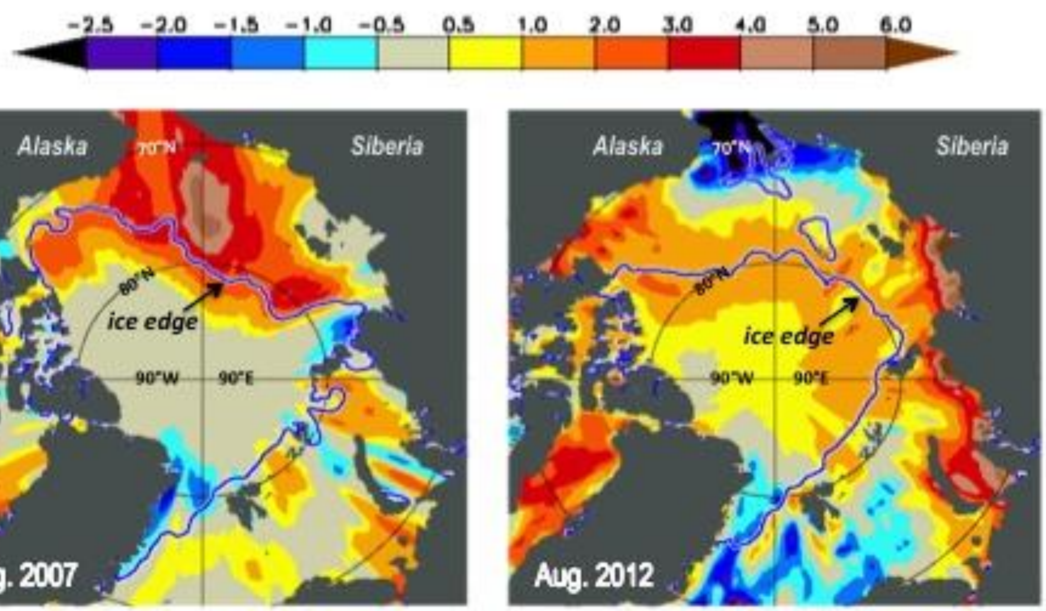


**Fig. 2.9.** Sea-surface temperature (SST) anomalies in August 2007 (left) and 2012 (right) relative to the August mean of 1982-2006. The anomalies are derived from satellite data according to Reynolds et al. (2007). The August mean ice edge (blue line) is also shown. Preliminary analysis and comparison to buoy data indicates that the extensive area of warm SST to the north of the ice edge is a processing artifact; these erroneous values arise from extrapolation of open water SSTs into the ice pack when concentration is low (Reynolds et al. 2007).

**Upper-ocean salinity.** Relative to the 1970s Environmental Working Group (EWG) climatology, the major upper-ocean salinity differences in 2011 (**Fig. 2.10**) are saltier central Nansen and Amundsen basins and a fresher Canada Basin, with the maximum freshwater anomaly centered in the BG. Another key feature of the upper ocean salinity, relative to climatology, is that the upper ocean is generally saltier around the southern boundary of the Canada Basin due to intensified upwelling at the basin boundaries associated with the large-scale wind-driven circulation in 2011 (**Figs. 2.6 and 2.7**). This circulation pattern shifted the position of the upper-ocean front between saltier waters of the Eurasian Basin and fresher Canada Basin waters. The magnitude of salinity difference from climatology is <1 in the Barents Sea, much smaller than in regions of the central Arctic basins. Upper-ocean salinity in 2011 is fresher than the 1970s climatology on the south side of the Barents Sea Opening (BSO) and to the east of Svalbard, while areas of the central Barents Sea and to the north of Svalbard exhibit higher salinity.

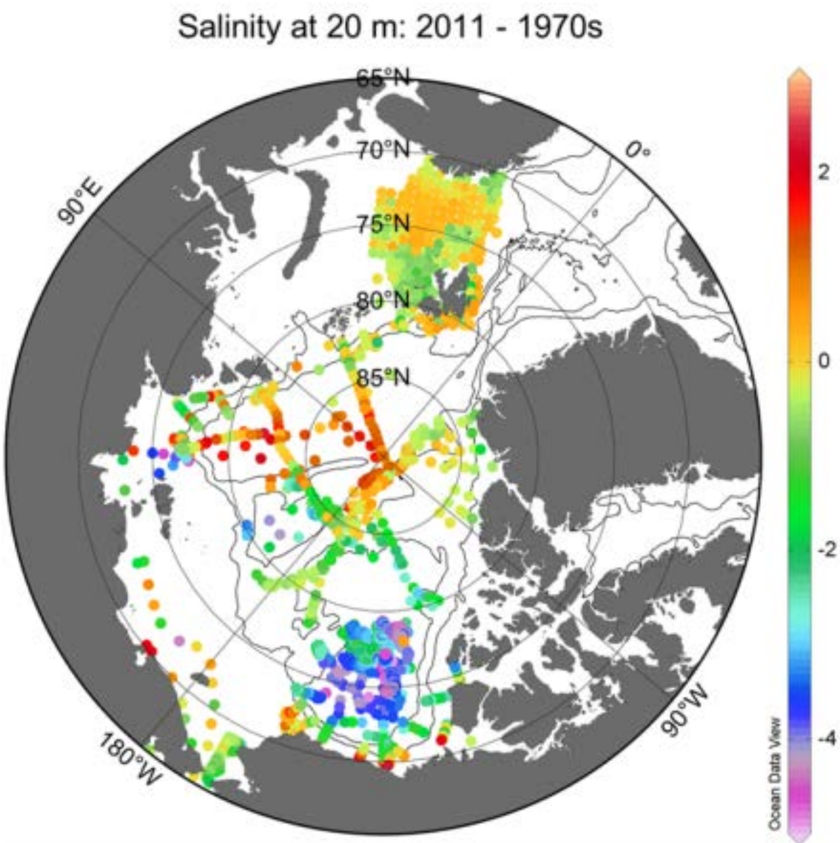


**Fig. 2.10.** Anomalies of salinity at 20 m depth in 2011 relative to 1970s climatology (see Fig. O.3, Proshutinsky et al. in Arctic Report Card 2011). Contour lines show the 500 and 2500m isobaths.

**Beaufort Gyre freshwater and heat content.** Arctic Ocean freshwater is concentrated in the BG of the Canada Basin, which has accumulated more than 5000 km$^3$ of freshwater during 2003 to 2012. This is a gain of approximately 25% (update to Proshutinsky et al. 2009) relative to climatology of the 1970s. This strong freshwater accumulation trend in the Beaufort Gyre is linked to an increase in strength over the past decade of the large-scale anticyclonic wind forcing (Proshutinsky et al. 2009; Proshutinsky and Johnson, 1997, updated). Shifts in major freshwater pathways also influence BG freshwater: Morison et al. (2012) show how increasing freshwater in the Canada Basin from 2005 to 2008 was balanced by decreasing freshwater in the Eurasian Basin when winds forced river runoff from the Russian sector to the Canada Basin. On shorter timescales, Beaufort Gyre freshwater is affected by oceanographic upwelling in response to easterly wind bursts in the southern Beaufort Sea; Pickart et al. (2012) demonstrated that the quantity of freshwater transported offshore during these storms can account for a significant fraction of the observed year-to-year variability in freshwater content of the Beaufort Gyre.

In 2012, the BG freshwater content was comparable to that in 2011, with preliminary estimates for the 2012 summer average freshwater content over the Beaufort Gyre region (relative to a salinity of 34.8) of 22.6 m (cf. the 2011 summer average: 21.9 m), **Fig. 2.11** (right panels). In 2012, the freshwater center appears to have shifted to the northwest, consistent with the large-scale wind forcing (**Fig. 2.7**, right panel). The BG heat content in 2012 also remained roughly comparable to 2011 conditions, with about 25% more heat on average in the summer compared to 1970s values (**Fig. 2.11**, left panels). As further hydrographic data become available from the 2012 field season, heat and freshwater content in the boundary regions in particular will be better constrained.

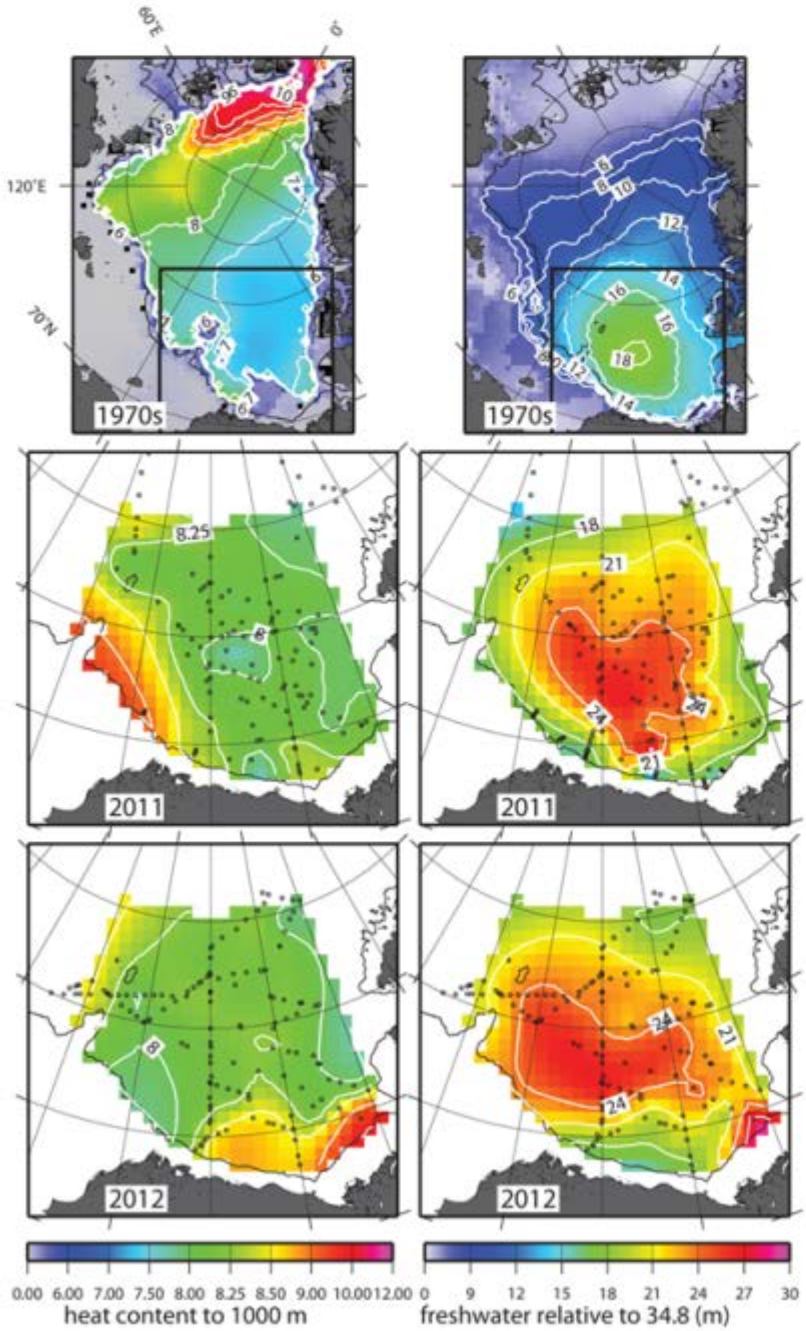


**Fig. 2.11.** Summer heat content ($1 \times 10^9$ J $m^{-2}$) and freshwater content (m). Heat content is calculated relative to freezing temperature in the upper 1000 m of the water column. Freshwater content is calculated relative to a reference salinity of 34.8. The top row shows heat and freshwater content in the Arctic Ocean based on 1970s climatology (Timokhov and Tanis 1997, 1998). The center and bottom rows show heat and freshwater content in the Beaufort Gyre (the region shown by the black boxes in the top row) based on hydrographic surveys (black dots depict hydrographic station locations) in 2011 and 2012, respectively; data are from the Beaufort Gyre Observing System (BGOS)/Joint Ocean Ice Studies (JOIS) expedition, http://www.whoi.edu/beaufortgyre/.

**The Atlantic Water Layer.** Warm water of North Atlantic origin, residing at depths below the Arctic halocline, is characterized by temperatures >0°C and salinities >34.5. In 2011, maximum Atlantic Water Layer temperature anomalies (relative to 1970s climatology) were generally highest on the Eurasian side of the Lomonosov Ridge, with maximum anomalies >2°C in Fram Strait (**Fig. 2.12**). Warming was less pronounced in the Canada Basin than in the Eurasian Basin. There was little to no temperature anomaly (<0.1°C) at the southeast boundary of the Canada Basin nor in the basin boundary regions adjacent to Greenland and the Canadian Archipelago. Atlantic Water temperatures are cooler now than in the 1970s in the vicinity of Nares Strait.

Atlantic Water properties in the Arctic are regulated by the Atlantic water inflow through Fram Strait and via the Barents Sea Opening. The warmest Atlantic Water temperatures in Fram Strait were observed in 2006, with a return of maximum temperatures to the long-term mean (2.7°C) by summer 2010 (**Fig. 2.13**). In summer 2011, the mean temperature remained close to that observed in 2010. In 2011 an anomalously warm and saline southward flow of Atlantic Water was observed in western Fram Strait (not shown), possibly indicating that the warm Atlantic Water anomaly, which had entered the Arctic Ocean in 2006, returned to Fram Strait after completing a loop in the Eurasian Basin. Atlantic Water temperatures in the Barents Sea Opening were also maximal in 2006, and declined through 2011. The largest volume fluxes of Atlantic Water through the Barents Sea Opening were measured in winter 2006, and were relatively low in the following years to 2011, although with strong seasonal variability; the lowest volume fluxes were observed in the spring and summer months.

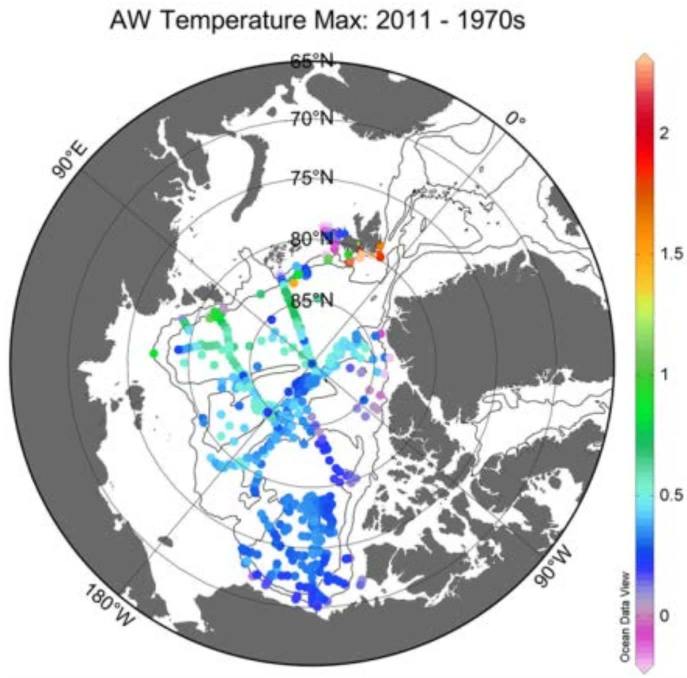


**Fig. 2.12.** Atlantic Water Layer temperature maximum anomalies in 2011 relative to 1970s climatology (see Fig. O.6, Proshutinsky et al., 2011). Contour lines show the 500 and 2500 m isobaths.

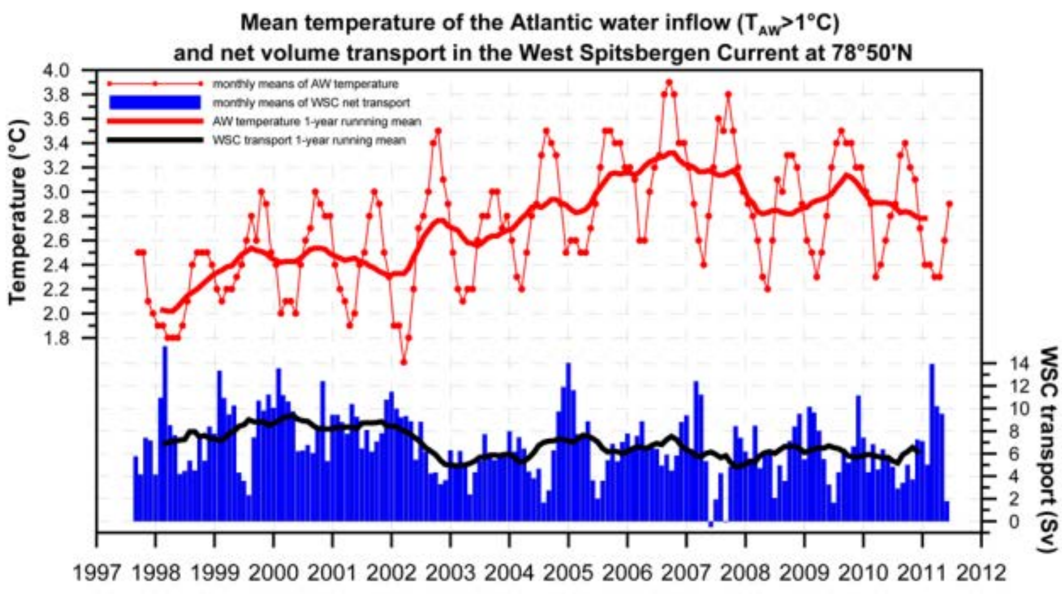


**Fig. 2.13.** Atlantic water (AW, defined here as having temperatures >1°C) mean temperature and the volume inflow in the West Spitsbergen Current (WSC), northern Fram Strait, measured by a mooring array at 78°50'N maintained since 1997 by the Norwegian Polar Institute and the Alfred Wegener Institute for Polar and Marine Research.

**The Pacific Water Layer.** The Pacific Water Layer in the Arctic originates from the Bering Strait inflow and resides in the Canada Basin at depths between about 50 and 150 meters. Pacific Water Layer properties and circulation patterns depend significantly on the prevailing winds, which tended to drive Pacific waters north and westward (**Figs. 2.6 and 2.7**) in 2011. Excessively high Pacific Water temperatures (warmer than $6^0$C) were observed on the Chukchi shelf/slope, Northwind Ridge region in September 2010 (during the R/V Mirai expedition, Kawaguchi et al., 2012) and later in winter 2010/2011 measured by Ice-Tethered Profilers. Data from Ice-Tethered Profilers that sampled in the central Canada Basin during 2004-2012 indicate no clear trend in Pacific water maximum temperatures (in the salinity range 29-33) over this time. There is significant interannual variability in both the salinity and temperature of Pacific Water in the central basin (temperature changes by as much as $1^{\circ}$C), with warming in recent years broadly congruent with freshening and the warmest temperatures observed in 2007 and 2010.

The properties of the Pacific Water inflow through the Bering Strait are measured by year-round in situ moorings, giving some information from 1990 and good coverage from 1999 to present. Recent results from these moorings (Woodgate et al., sub. 2012) show that the 2011 flow through the strait is ~1.1 Sv, significantly greater than the generally accepted climatological value of ~ 0.8 Sv (Roach et al., 1995), almost 50% more than the 2001 value of ~0.7 Sv (Woodgate et al., 2006), and comparable to previous high flow years of 2007 and 2004 (Woodgate et al., 2010).

The 2011 Bering Strait heat flux (~ $5x10^{20}$ J relative to $-1.9^{\circ}$C, the freezing point of Bering Strait waters) is comparable with the previous record high in 2007. This high heat flux is due to increased flow and warming of the lower layers of the water column in the strait. Interannual change in these lower layer temperatures does not correspond to interannual change in satellite sea surface temperatures (SSTs) in the region (Woodgate et al., sub. 2012). A preliminary estimate of the freshwater flux through the strait relative to a salinity of 34.8 (Woodgate et al., submitted 2012) suggests the 2011 annual mean is 3000-3500 $km^3$, roughly 50% greater than 2001 and 2005 values; interannual variability of the freshwater flux appears to be larger than the interannual variability in the other major freshwater sources to the Arctic (rivers and net precipitation). The ~ 50% increase in oceanic fluxes through the Bering Strait between 2001 and 2011 is mostly due to an increase in the far-field pressure head forcing of the flow (Woodgate et al., sub 2012).

**Sea Level**

In 2011, sea level (SL) along the Siberian coast increased relative to previous years (**Fig. 2.14**). This caused an increase, to $2.66 \pm 0.41$ mm $yr^{-1}$, in the estimated rate of SL rise since 1954 averaged over nine tide gauge stations located along the coasts of the Kara, Laptev, East Siberian and Chukchi seas (after correction for glacial isostatic adjustment; Proshutinsky et al. 2004). Until the late 1990s, sea level atmospheric pressure accounted for more than 30% of variability in SL (Proshutinsky et al. 2004) due to the inverse barometer effect. In contrast, from 1997 to 2011, mean SL has generally increased while sea level atmospheric pressure has remained stable. The tendency toward SL rise in this period may be due to steric effects associated with a reduction of sea ice and ocean surface warming (Henry et al. 2012). After 2008, SL decreased to a minimum in 2010 and then increased in 2011. These variable changes likely result from a combination of many forcing factors. One important factor is associated with Ekman transport directed toward coastlines; in 2011, Ekman transport drove positive sea level anomalies along the Siberian coast.

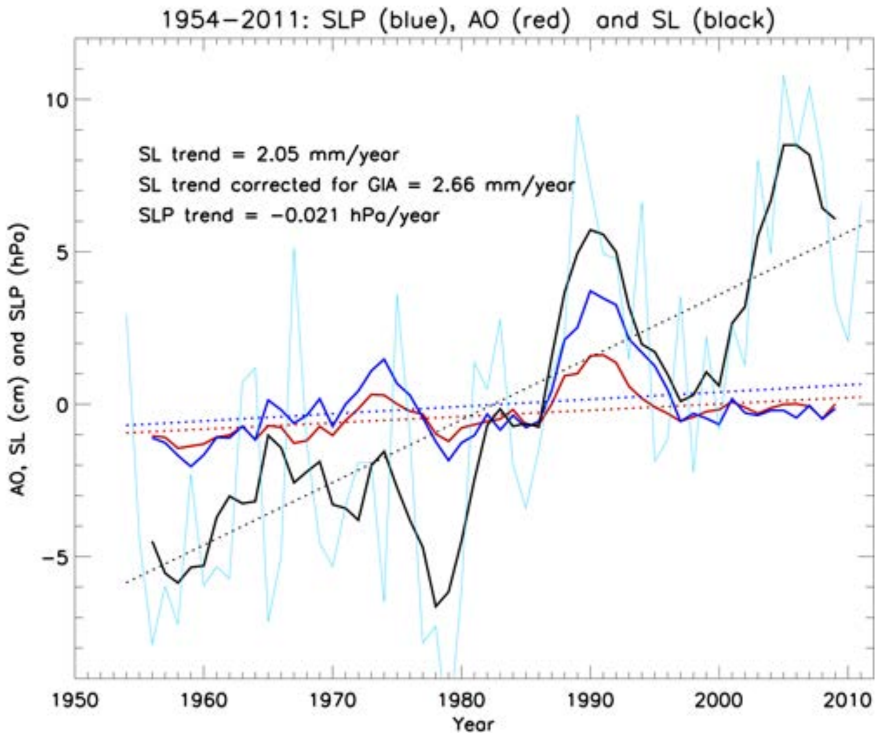


**Fig. 2.14.** Five-year running mean time series of: annual mean sea level (SL) at nine tide gauge stations located along the coasts of the Kara, Laptev, East Siberian and Chukchi seas (black line; the light blue line shows the annual average); anomalies of the annual mean Arctic Oscillation index (AO, Thompson and Wallace, 1998) multiplied by 3 for easier comparison with other factors (red line); sea surface atmospheric pressure (sea level pressure, SLP) at the North Pole (from NCAR-NCEP reanalysis data) multiplied by -1 to show the inverse barometer effect (dark blue line). Dotted lines depict trends for SL (black), AO (red) and SLP (blue).

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# Arctic Report Card 2012

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**Sections**

# 3. Marine Ecosystem

## 3.1 - Arctic Ocean Primary Productivity and Nutrient Variability

Karen E. Frey[1], Kevin R. Arrigo[2], William J. Williams[3]

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### Highlights

- Massive phytoplankton blooms beneath a 0.8–1.3 m thick, fully consolidated (yet melt-ponded) sea ice pack were observed in the north-central Chukchi Sea in July 2011. The blooms extended >100 km into the ice pack and biomass was greatest (>1000 mg C $m^{-3}$) near the ice-seawater interface, with nutrient depletion to depths of 20–30 m.
- New satellite remote sensing observations show (a) the near ubiquity of ice-edge blooms across the Arctic and the importance of seasonal sea ice variability in regulating primary production, and (b) a reduction in the size structure of phytoplankton communities across the northern Bering and Chukchi seas during 2003–2010.
- A unique marine habitat containing abundant algal species in so-called "melt holes" was observed for the first time in perennial sea ice in the central Arctic Ocean.
- During the last decade, the intensification of the Beaufort Gyre has pushed the nutricline deeper, and the subsurface chlorophyll maximum that was at 45 m in 2002 has deepened to 60–65 m in 2008–2012.

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Sea ice melt and breakup during spring strongly drive primary production in the Arctic Ocean and its adjacent shelf seas by enhancing light availability as well as increasing stratification and stabilization of the water column. Previous large-scale, synoptic estimates of primary production in the Arctic Ocean typically assume that phytoplankton in the water column beneath the sea ice pack is negligible. However, massive phytoplankton blooms beneath a 0.8–1.3 m thick, fully consolidated (yet melt-ponded) sea ice pack were observed in the north-central Chukchi Sea in July 2011 (Arrigo et al., 2012) (**Fig. 3.1**). These blooms (primarily consisting of pelagic diatoms of the genera *Chaetoceros*, *Thalassiosira*, and *Fragilariopsis*, indicating this was not a remnant sea ice algal bloom) extended from the ice edge to >100 km northward into the pack ice. Biomass was greatest (>1000 mg C $m^{-3}$) near the ice/seawater interface and was associated with large nutrient deficits in the upper 25–30 m of the water column beneath the ice (**Fig. 3.2**). Although it is not clear whether these under-ice phytoplankton blooms are a new phenomenon, a shift away from snow-covered multi-year ice (typical of these areas in the 1980s) towards a thinner, more melt-ponded sea ice cover (typical of current conditions) may enhance light transmittance (Frey et al., 2011) necessary for primary production, given the presence of sufficient nutrients. Given these new observations, previous estimates of annual primary production in waters where these under-ice blooms develop may be ~10-fold too low (Arrigo et al., 2012)

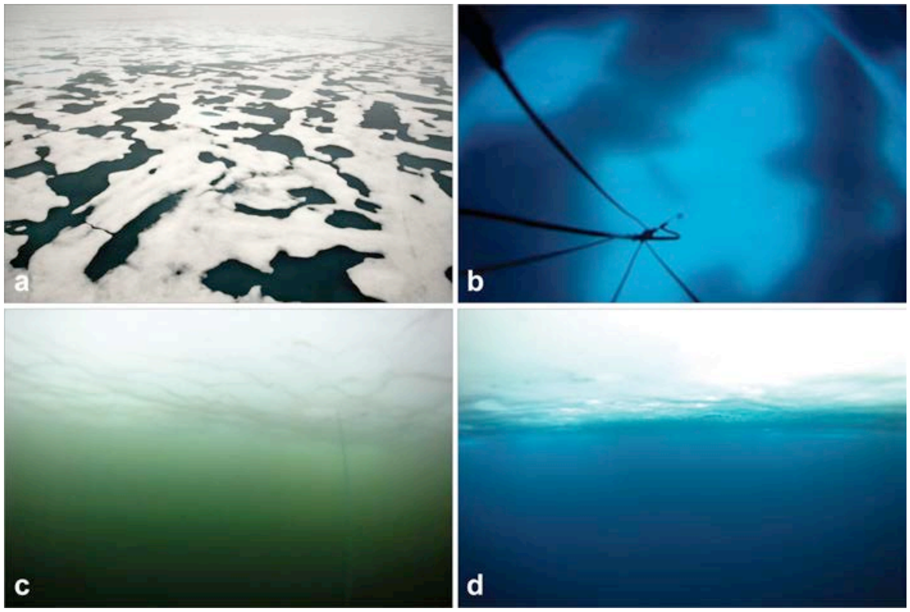


**Fig. 3.1.** Under-ice phytoplankton blooms observed during July 2011 in the north-central Chukchi Sea and associated: (a) aerial view of surface melt pond distributions; (b) view from ~20 m under the sea ice looking up through a melt pond; (c) massive phytoplankton bloom directly under the sea ice; and (d) non-bloom waters under sea ice further east in the Chukchi Sea during July 2011. Photographs by Karen Frey.

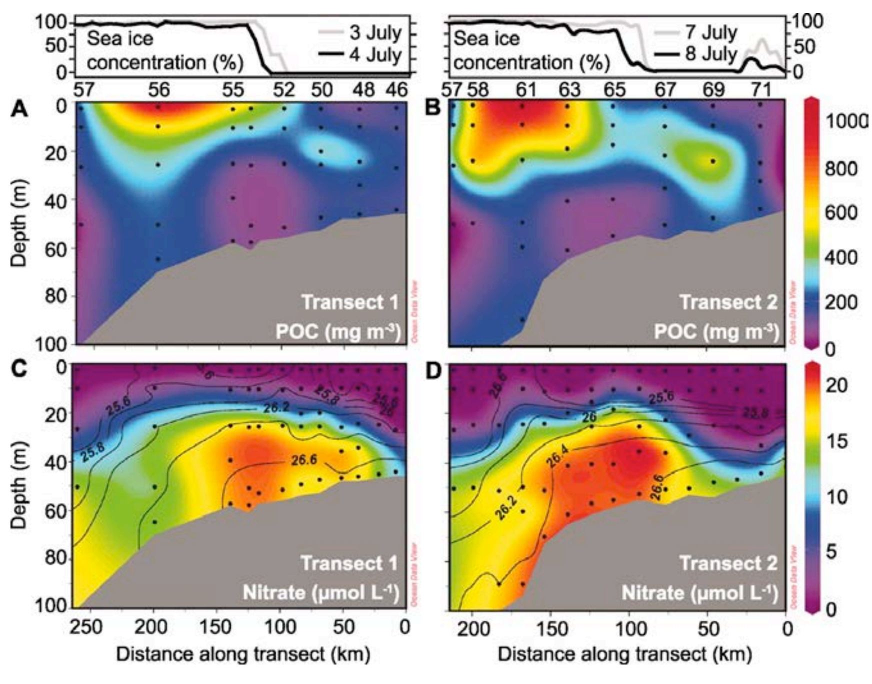


**Fig. 3.2.** Under-ice phytoplankton blooms observed during July 2011 along two transects in the north-central Chukchi Sea and associated measurements: (a) Particulate organic carbon (POC) and (c) nitrate from Transect 1; and (b) POC and (d) nitrate from Transect 2. From Arrigo et al. (2011).

Additional insights into Arctic Ocean primary production have been derived from satellite remote sensing observations, including information related to ice-edge blooms, size structure of phytoplankton communities, and subsurface chlorophyll maxima. Perrete et al. (2011) show strong connections between seasonal sea ice retreat and primary production, where these near-ubiquitous ice-edge blooms across the pan-Arctic are observed in 77–89% of locations where adequate data exist. These bloom are typically observed to peak within 20 days of ice retreat and average >1 mg $m^{-3}$ (with major blooms >10 mg $m^{-3}$). Ice-edge blooms are less common in areas of early sea ice melt (at lower latitudes) and their contributions to annual primary productivity rates are reduced owing to the long periods available for open-water blooms. At higher latitudes, in contrast, it is shown that primary productivity rates at the ice-edge may be 1.5–2 times greater than those in open-water conditions. Fujiwara et al. (2011) have developed a new satellite-based algorithm for deriving the size structure of phytoplankton communities across the northern Bering and Chukchi seas. Through these analyses, it is suggested that phytoplankton size is inversely related to variability in sea surface temperature. Furthermore, during the period investigated (2003–2010), the derived phytoplankton size index was shown to significantly decrease (likely related to limitations in nutrients), which is an important finding in the context of carbon turnover rates and the vertical pathways of carbon flow (Reigstad et al., 2011).

In addition to phytoplankton primary production, sea ice algal production is also important to consider in the overall Arctic Ocean system. A unique marine habitat for sea ice algae in so-called "melt holes" was observed for the first time in perennial sea ice in the central Arctic Ocean (Lee et al., 2011; Lee et al., 2012). The melt holes are formed in thinning sea ice where surface melt ponds completely penetrate the ice and connect to the underlying seawater. These open ponds have higher nutrient concentrations than closed surface melt ponds owing to the connection with the seawater; consequently, this newly observed marine habitat contains abundant algal species (mainly *Melosira arctica*, constituting >95% of the biomass) known to be important for zooplankton consumption. Furthermore, the accumulation of these algal masses attached to refreezing ice in late summer may provide an important food supplement for higher trophic levels as the ecosystem enters winter. Lee et al. (2012) estimate that the total carbon production in melt ponds in Arctic sea ice amounts to ~2.6 Tg C $yr^{-1}$, which constitutes <1% of recent total production in the whole Arctic Ocean. However, this fraction may be significantly higher when only considering ice-covered portion of the Arctic Ocean. Lee et al. (2011) suggest that continued warming and decreases in sea ice extent and thickness may result in a northward extension of these open pond habitats and even their potential disappearance as perennial sea ice cover becomes more scarce across the Arctic Ocean.

Important shifts in nutrient availability over recent years have also driven significant changes in primary production of Arctic Ocean waters. A subsurface chlorophyll maximum stretches across the Beaufort Gyre Region of the Canada Basin in summer. It exists at the top of the nutricline, a location that is as close to sunlight as possible while nutrients are still present (McLaughlin and Carmack, 2010). The Beaufort Gyre has intensified dramatically since 2002 owing to Ekman convergence, with a particularly large jump in the winter of 2007/2008. This intensification has pushed the halocline down, as indicated by the deepening of the 33.1 psu isohaline (**Fig. 3.3a**). Additional melting of sea ice during this time has also resulted in lower surface salinities (**Fig. 3.3b**) and increased upper halocline stratification (**Fig. 3.3c**). The combination of a deeper halocline and stronger stratification has pushed the top of the nutricline farther away from sunlight and reduced nutrient availability, thus stressing phytoplankton at the subsurface chlorophyll maximum (McLaughlin and Carmack, 2010). The subsurface chlorophyll maximum is correspondingly deeper (**Fig. 3.3d**). Data from 2012 are similar to 2008–2010, and consistent with a slight relaxation of the Beaufort Gyre.

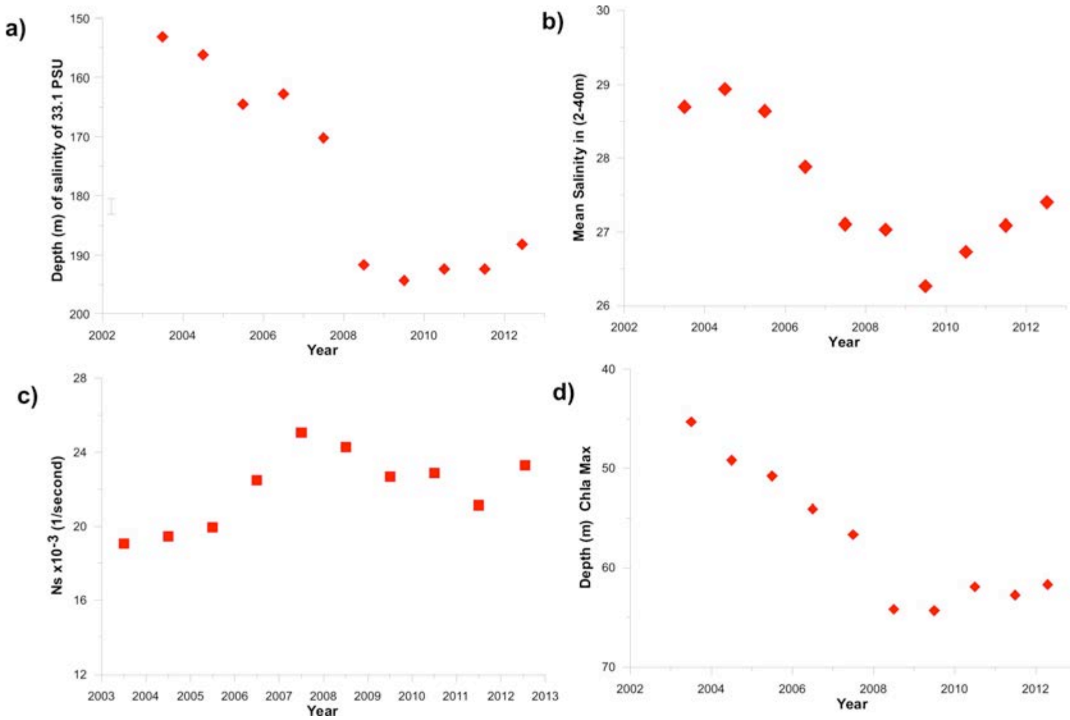


**Fig. 3.3.** Time series of average near-surface properties of the Beaufort Gyre Region of the Canada Basin as measured by the Joint Ocean Ice Studies expeditions aboard the *CCGS Louis S. St-Laurent* in collaboration with the Woods Hole Oceanographic Institution's Beaufort Gyre Exploration Project. depth of the 33.1 psu isohaline (a), mean salinity over the depth range 2–40 m (b), mean stratification due to salinity over the depth range 5–100 m (c), and depth of the subsurface chlorophyll maximum (following McLaughlin and Carmack, 2010) (d).

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# 3.2 - Cetaceans and Pinnipeds (Whales and Seals)

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**Highlights**

- Species richness for core Arctic marine mammals is highest in 3 regions: Baffin Bay, Davis Strait and the Barents Sea, where nine of 11 species are present. Most other regions have seven or eight core species, while the Beaufort Sea and the Sea of Okhotsk regions have only six species.
- Results of the first coordinated year-round sampling of underwater acoustic marine mammal habitats at two sites in the High Arctic – Fram Strait and on the Chukchi Plateau – during International Polar Year 2007-2009 are now available.
- Two acoustic recorders in Fram Strait documented Spitzbergen's bowhead whales singing almost continuously through the winter.

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**CAFF Arctic Biodiversity Assessment (ABA)**

Arctic marine mammals are widely considered to be icons of climate change. However, no comprehensive studies have examined available data on population abundance, distribution and trends across the Arctic. In 2011, the "Arctic Biodiversity Assessment - Status and Trends" (ABA) was launched by the Arctic Council Working Group on Conservation of Arctic Flora and Fauna (CAFF) to synthesize and assess the status and trends of biological diversity in the Arctic. The report is an international collaboration among marine mammal scientists from all Arctic countries, which serves to inventory and update the status and trends of all stocks of Arctic marine mammals. The ABA summarizes what is known about population sizes, trends, and distributions for species that inhabit sub-Arctic and Arctic waters. It also discusses implications of data gaps on various species given predictions of continued sea ice loss and climate warming – see the *Sea Ice* essay for more information about sea ice loss.

In total, 35 marine mammal species that inhabit or seasonally use Arctic waters were reviewed in the ABA and assessed in the context of 12 marine regions in low or high Arctic waters. Species were considered in two categories: (1) species that occur north of the Arctic Circle for most of the year and depend on the arctic ecosystem for all aspects of life (n=11 "core" Arctic marine mammals) (Table 3.1), and (2) selected sub-arctic species whose life histories include seasonal migration to and occupation of arctic waters, yet do not depend on the arctic ecosystem for some parts of the year (n=24 species). Authors calculated species richness (number of species present in different regions) and summarized available data on changes in distribution, population abundance estimates and available trends for marine mammals inhabiting the circumpolar Arctic. Species richness for core Arctic marine mammals is highest in 3 regions: Baffin Bay, Davis Strait, and the Barents Sea, where nine of 11 species are present (**Fig. 3.4**); most other regions have seven or eight core species, while the Beaufort Sea and the Sea of Okhotsk regions have only six species. The final CAFF ABA is due in spring 2013.

**Table 3.1. List of core marine mammal species considered in the CAFF ABA.**

| | | |
|---|---|---|
| Arctic | Narwhal | *Monodon monoceros* |
| | Beluga whale | *Delphinapterus leucas* |
| | Bowhead whale | *Balaena mysticetus* |
| | Ringed seal | *Phoca hispida* |
| | Bearded seal | *Erignathus barbatus* |
| | Walrus | *Odobenus rosmarus* |
| | Polar bear | *Ursus maritimus* |
| Sub-Arctic | Spotted seal | *Phoca largha* |
| | Ribbon seal | *Phoca fasciata* |
| | Harp seal | *Pagophilus groenlandicus* |
| | Hooded seal | *Cystophora cristata* |

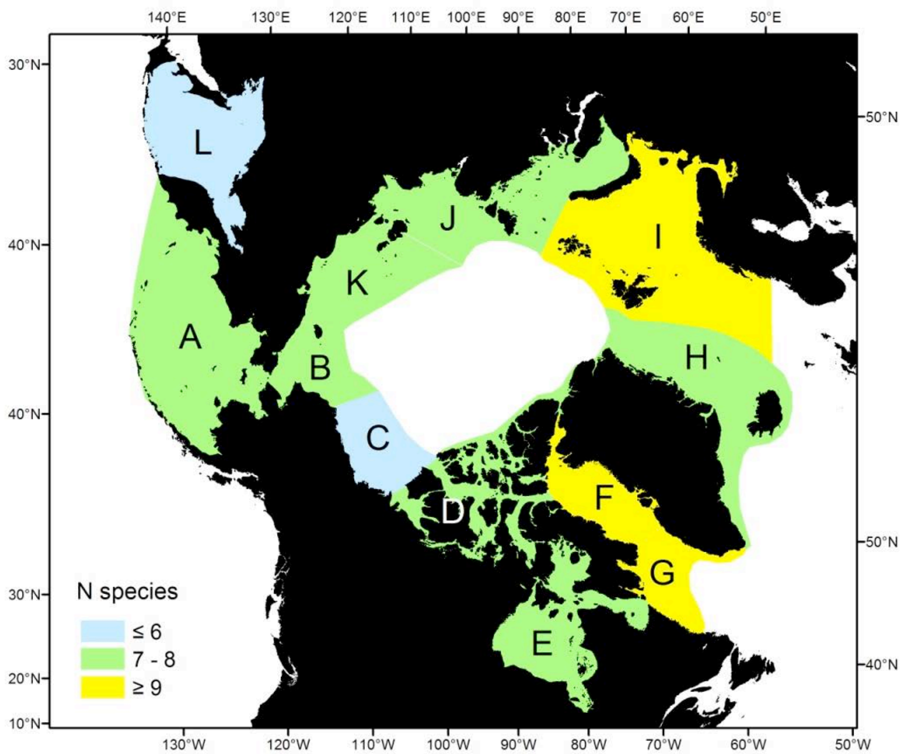


**Fig. 3.4.** Species richness of core marine mammals (n = 11) in high and low Arctic waters quantified for 12 regions: (A) Bering Sea, (B) Chukchi Sea, (C) Beaufort Sea, (D) Arctic Archipelago, (E) Hudson Bay and Foxe Basin, (F) Baffin Bay, (G) Davis Strait, (H) East Greenland and Iceland, (I) the Barents Sea, (J) the Laptev and Kara Seas, (K) East Siberian Sea, and (L) Okhotsk Sea. Source: CAFF (2013).

**Acoustic Ecology**

Several recent studies of Arctic marine mammals using autonomous recorders have provided new information on species seasonality and acoustic environments in the Arctic. Moore et al. (2012) report on an initiative from the International Polar Year (2007-2009), when acoustic recorders were deployed on oceanographic moorings in Fram Strait and on the Chukchi Plateau. This was the first coordinated year-round sampling of underwater acoustic habitats at two sites in the High Arctic.

Distinctly different acoustic habitats were found at each site, with the Fram Strait being acoustically complex compared to the Chukchi Plateau. In Fram Strait, calls from bowhead whales (*Balaena mysticetus*) and a variety of toothed whales (odontocetes) were recorded year-round. Surprisingly, calls from sub-Arctic whales, including blue (*Balaenoptera musculus*) and fin whales (*B. physalus*), were recorded from June to October and August to March. At the Chukchi Plateau site, beluga (*Delphinapterus leucas*) and bowhead whale calls were recorded primarily from May to August. Ribbon seal (*Phoca fasciata*) calls were detected in October–November, and no marine mammal calls were recorded from December to February.

Differences in acoustic habitats between the two sites were related to contrasts in sea ice cover, temperature, patterns of ocean circulation and contributions from anthropogenic noise sources. Stafford et al. (2012) reported on bowhead whales singing almost continuously through the winter from data from two recorders in Fram Strait. Peak levels of song production coincided with the period of lowest water temperature, high ice concentration, and almost complete darkness. Repeated call sequences and songs were detected nearly every hour from early November 2008 through late April 2009 on the western Fram Strait recorder and more than 60 unique songs were recorded from October 2008 to April 2009. The authors concluded that western Fram Strait may be a wintering ground or potential mating area for bowhead whales.

**Updates on Arctic marine mammal movements and distribution relative to sea ice**

**Bowhead whales:** Wheeler et al. (2012) used governmental, private and historical whaling location datasets on eastern Canadian Arctic (ECA) bowhead whales to create a monthly ecological niche factor analysis for the 'reduced-ice' period (June to October) to determine habitat suitability. Multiple habitat suitability models were developed to create a composite map of predicted high suitability habitat for 5 months. Six critical habitats were identified around Baffin Island, Hudson Strait, and the Labrador coast which were supported by recent scientific evidence and Inuit knowledge. The study provides resource managers with a timely tool for population recovery, conservation, and protection.

Laidre and Heide-Jørgensen (2012) examined the movements of two co-occurring baleen whales, the bowhead whale and the humpback whale (*Megaptera novaeangliae*), in Disko Bay, West Greenland using satellite telemetry. Data were collected from tagged bowhead (n=49) and humpback whales (n=44) during the transition from sea ice breakup to open water between 2008 and 2010. The departure of bowhead whales from Disko Bay coincided almost precisely with the arrival of humpback whales, and during a brief period of overlap, the two species used different areas and habitat. A significant trend in later spring migration departure date was found for bowhead whales, with an approximate 2-week difference in departure between 2001 and 2010.

**Beluga whales:** Goetz et al. (2012) developed predictive habitat models for the endangered population of beluga whales in Cook Inlet, Alaska, using an analysis based on data from aerial surveys conducted between 1994 and 2008. They found there is a greater probability of belugas being present closer to rivers with Chinook salmon runs, rivers with medium flow accumulation (assessed using quartile values of each river), tidal flats, and areas with sandy coastlines. Probability of beluga presence decreased closer to rivers with chum salmon, rivers with high flow accumulation, local communities, oil development, and coastal areas with rocky substrate. Distinguishing suitable habitat is integral to the sustainability and recovery of the Cook Inlet beluga whale population.

Bailleul et al. (2012) report on differences in migration timing for beluga whales in Eastern Hudson Bay (EHB) and suggested a mechanism by which environmental conditions determine habitat use and migration patterns. Later migration date departures were observed for whales in 2002 and 2003, when warmer and spatially more heterogeneous sea temperatures prevailed during summer. This was in contrast to 2004, which was the coldest summer since the 1990s. The authors suggest later departures may become more typical for beluga whales as temperatures continue to increase.

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## 3.3 - Arctic Benthos

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**Highlights**

- Recent findings on temporal trends in the benthic system include: species range changes in sub-Arctic seas and on inflow shelves; changes in feeding guild composition in the deep Fram Strait; reduction of benthic biomass in the Barents and northern Bering seas; no apparent change in infaunal biomass in the Kara Sea.
- Results from Greenland, and the northern Bering and Chukchi seas show spatial and temporal differences and variability in invertebrate growth, energy budgets and resulting biomass that are related to variation in seasonal sea ice dynamics, temperature and food supply.
- Greatly improved benthic species inventories for Iceland, Greenland and the Russian Arctic show upwards of 1000 to >3000 benthic species per region.
- Contrary to long-standing belief, terrestrial carbon significantly contributes to benthic food webs on the river-influenced Beaufort Sea shelf.

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**Introduction**

Macrobenthic infauna act as long-term integrators of overlying sediment processes. They remain relatively stationary in the sediment and their community patterns are thus directly affected by export production from the overlying water column. The distribution, abundance and biomass of infauna vary by region and are related to water mass characteristics and current patterns.

This report on the Arctic benthos is pan-Arctic in scope and organized by region. International members of the benthic expert group of the Arctic Council's Circumpolar Biodiversity Monitoring Program under CAFF (Conservation of Arctic Flora and Fauna) summarized new key findings in their regions. The scope of research and nature of those findings vary among regions.

**Northern Bering Sea and Chukchi Sea**

Bivalves, amphipods, and polychaetes dominate the infaunal biomass south of St. Lawrence Island in the northern Bering Sea, where time series data indicate a decline in overall station biomass over the last decades (**Fig. 3.5**); amphipods and bivalves dominate in the central region from St. Lawrence Island to Bering Strait, and bivalves and polychaetes dominate in the southern Chukchi Sea to the slope region of the Canada Basin (Bluhm and Grebmeier, Arctic Report Card 2011).

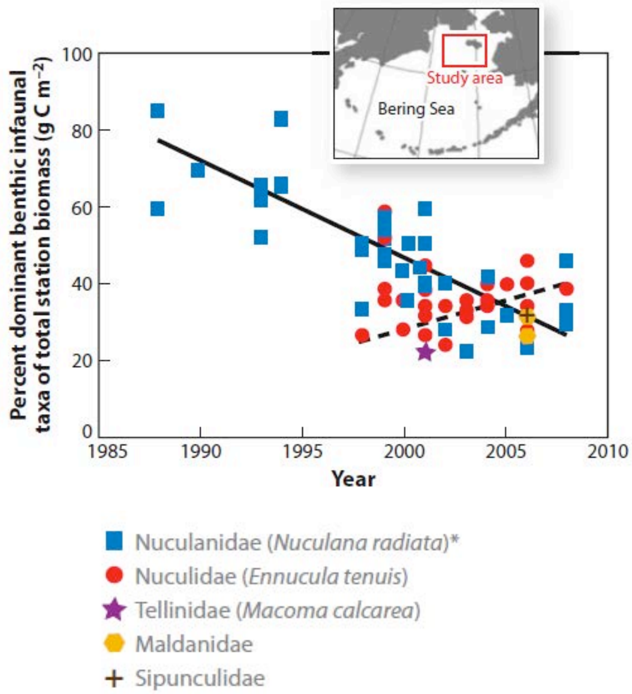


**Fig. 3.5.** Example of change in infaunal benthos on Arctic shelves. Decrease (solid black line) in relative contribution of bivalve, *Nuculana radiata*, to total infaual biomass south of St. Lawrence Island. The species is important prey for diving sea ducks in the region. From Grebmeier (2012).

The nutrient- and phytoplankton-rich water that is transported northwestward through Bering Strait is a major driver of the high benthic faunal productivity of the south-central Chukchi Sea. Macrobenthic infaunal biomass in the south-central Chukchi Sea ranges from 24 to 59 g C $m^{-2}$ and exceeds 120 g C $m^{-2}$ at the 'hot-spot'' just northwest of Bering Strait (citations in Grebmeier 2012). This southeast Chukchi infaunal assemblage is dominated by tellinid and nuculid bivalves*,* ampeliscid and lysianassid amphipods (Grebmeier 2012). In contrast to the very productive western side of the system, benthic communities to the east, which are strongly influenced by Alaska Coastal Water, are more patchy, variable in composition and typically of very low biomass (<10 g C $m^{-2}$, but occasionally ranging up to higher values of 12–23 g C $m^{-2}$), but are characterized by higher diversity. As this Pacific water mass flows north into the central Chukchi Sea, the  it becomes progressively depleted of nutrients and phytoplankton. Perhaps not surprisingly, then, infaunal biomass declines from the southern Chukchi Sea ''hot-spot'' to the central Chukchi Sea, with biomass decreasing to <10 g C $m^{-2}$ (Bluhm and Grebmeier 2011: Figure 1,).

Winter-transformed Bering Sea water flows through Herald Valley and Herald Trough (located in the western and central Chukchi Sea, respectively), where infaunal communities are dominated by maldanid, lumbrinerid, and nephtyid polychaetes. Bivalves and polychaetes dominate the infaunal community of the northern Chukchi Sea, where average infaunal benthic biomass is a moderate 5–15 g C $m^{-2}$, although recent studies indicate high benthic biomass in upper Barrow Canyon. On the upper slope (200–1000 m depth) and extending down into the

Canada Basin, the benthic community becomes foraminifera-dominated, with biomasses of <5 g C $m^{-2}$ (citations in Grebmeier 2012).

**Beaufort Sea**

Both the International Polar Year and ongoing and planned fossil fuel development recently sparked several new benthic research projects in the Beaufort Sea. Studies continue, but first results confirm trends found in the 1970s when the area's benthos was last surveyed. Epibenthic invertebrate biomass dominates significantly over demersal fish biomass (>90% in trawl hauls versus <10%, respectively) (Rand and Logerwell 2011) with dominant epibenthic taxa (brittle stars, other echinoderms, and crustaceans) similar to those on other Arctic shelves. Biomass generally decreased from west to east in US waters, but high variability was observed farther east as well as hot spots in the Cape Bathurst polynya. Benthic remineralization in the region increases after ice break-up, although interactions of food availability, benthic biomass and remineralization are complex and often more spatially variable than seasonally (Link et al. 2011). A new ice algal biomarker detected in a variety of benthic taxa supports previous research that suggested that ice algae contribute significantly to the nutrition of Arctic shelf benthos (Brown and Belt 2012). In the shallow coastal lagoons of the Beaufort Sea, terrestrial carbon can add substantially to the productivity of marine nearshore Arctic habitats, as reflected in terrestrial stable isotopic signatures and high prevalence of benthic omnivorous and detritivorous fauna. Comparatively short-lived and fast colonizing fauna dominate the benthic community in those lagoons where they are preyed upon by water fowl, fish and seals (Dunton et al. 2012).

**Canadian Arctic**

The establishment of ecologically or biologically significant marine areas (EBSA) through application of scientific criteria has been promoted by the Convention on Biological Diversity (decision IX/20) and will be a baseline for sustainable use and development of the marine ecosystem in the future. While benthic data were not included in EBSA design in Canada, Kenchington et al. (2011) used the Canadian identification criteria (uniqueness/rarity; aggregation; fitness consequences; with naturalness and resilience used to prioritize amongst sites identify possible EBSAs) based on benthic attributes for the Canadian Arctic (**Fig. 3.6**). Specifically, benthic diversity and biomass, the density of coral and sponge beds, and benthic remineralization and sediment pigment concentration were used to identify benthic EBSAs for the Hudson Bay Complex, Eastern Arctic and Western Arctic regions. High concentrations of soft corals and sponges are observed in the Hudson Strait compared to Hudson Bay. In the Eastern Arctic, the Baffin Bay-Davis Strait areas are characterized by important aggregations of sea pens, large gorgonian corals and sponges (Kenchington et al. 2010). Franklin Bay and the Prince of Wales Strait in the Canadian Arctic Archipelago were also suggested as benthic EBSAs. Benthic assemblages differ among seven regions on the Canadian Arctic shelf and with taxonomic diversity higher in eastern regions than in the central and western Canadian Archipelago. Currently known macrobenthic (infaunal) species richness in the Canadian Arctic is 992 taxa, not much different from the more sampled Atlantic Canada (1044 taxa) and Pacific Canada (814 taxa) regions (Archambault et al. 2010). Lancaster Sound and the North Water Polynya areas support particularly high benthic diversity, benthic biomass and high benthic boundary fluxes. Lancaster Sound also supports important populations of Pennatulacean sea pens with the continental slope off Baffin Bay.

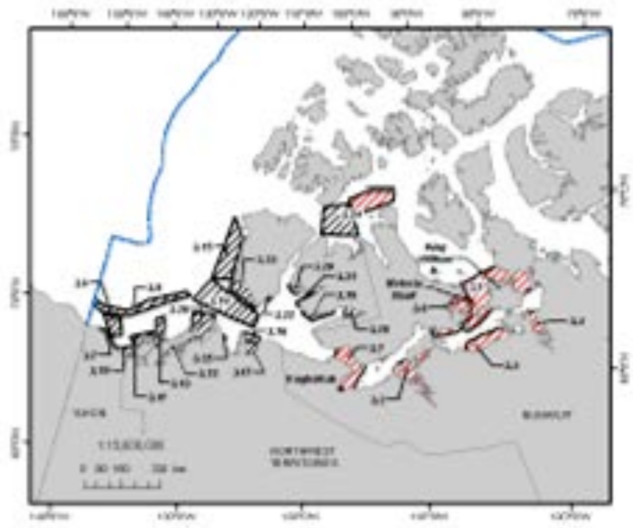

**Fig. 3.6.** Example for identification of Ecologically and Biologically Significant Areas (EBSAs) for mega- and macrobenthos in the Canadian Arctic. From Kenchington et al. 2011. *(higher resolution image will be provided once available)*

**Greenland**

The poorly studied benthic invertebrate fauna off Greenland (i.e., Baffin Bay, Davis Strait, Denmark Strait and Greenland Sea) mostly lacks historical data on basic ecosystem components necessary to document the state of the environment and potential future changes. However, recent research initiatives have been undertaken as a consequence of ongoing and predicted climate changes, oil and mineral exploration, and an increasing market demand for environmental certification of industrial fisheries. On a species level, geographic and inter-annual differences in the growth of dominant coastal primary and secondary producers are related to variation in seasonal sea ice dynamics (Krause-Jensen et al. 2012). Similarly, the energy budget of commercially exploited scallops is negatively affected by increasing temperature (Blicher et al. 2010). Exploring such relationships (**Fig. 3.7**) is critical when considering direct economic implications of climate change. On a community level, data are too scarce to document such relationships, although a recent macrozoobenthic survey on a shallow bank in Davis Strait did not show any difference in species richness between 1976 and 2009. These recent studies in West Greenland (Baffin Bay and Davis Strait, 60°N to 78°N) have documented the presence of highly diverse macrozoobenthic communities and also suggest that the benthic environment plays a key role in carbon flux in the regional shelf and coastal systems. Several organisms recovered during these surveys are potentially new to science.

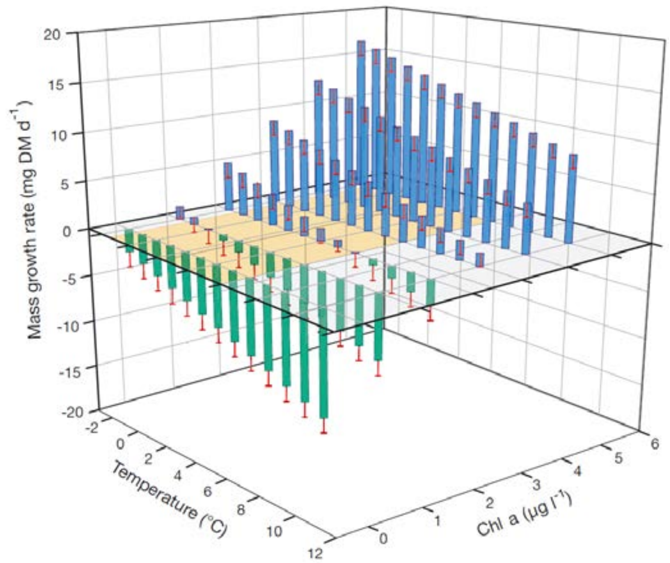


**Fig. 3.7.** Example of effect of environmental variables (temperature and chlorophyll a) on growth rate of the commercial bivalve *Chlamys islandica* in Greenland waters (Blicher et al. 2010). Red bars show negative effects of increasing C:N ratios (to 14). Yellow shade marks the range of values encountered in the field study.

### Iceland

Within the 200 mile, 750,000 km$^2$ economic zone of Iceland the occurrence of over 1,900 benthic invertebrates species of all major phyla and classes has been recorded over the past few years as a result of the BIOICE program. This area includes a central part of the Greenland-Scotland-Ridge, which forms an isolating barrier between the abyssal plains of the North Atlantic and the Arctic oceans (Dauvin et al. 2012). Near-bottom water temperature and the number of benthic species vary greatly north and south of the ridge. Although by far the lowest species diversity occurred in the deeper parts of the Arctic Ocean (>600 m) north of the ridge, a significant portion of endemic species were found in the Arctic fauna, mostly confined to lower taxonomic levels (Briggs and Bowen 2012). As a result of climate warming, near-bottom water temperature on the shelf around Iceland has been increasing over the last decades (Sólmundsson et al. 2007). Specifically, a ~2-3°C temperature increase on the shelf-areas south and west of Iceland during the last three decades has affected benthic species distributions. An example is the angler fish, *Lophius piscatorius*, whose distribution has expanded in Icelandic waters with increased near-bottom water temperature.

### Barents Sea

As an inflow shelf, the Barents Sea ecosystem is particularly strongly influenced by inter-annual and seasonal climate-driven variations, including factors such as ice cover and the strength of inflowing Atlantic water. Water temperatures have increased by 1.5$^o$C since the 1970s, with the strongest increase in the northern Barents Sea. Historical benthic data show that dominant boreal-arctic species have their temperature optimum close to the long-term temperature mean, and that any deviations from that mean will have negative impacts on abundance, reproductive success and change distribution range (Anisimova et al. 2011 and references therein). This negative effect is higher in temperatures above than below the long-term mean temperature. The average infaunal biomass in years around the long-term mean temperature is 100-147 g wet weight/$m^2$. Trawling impact and warming are thought to be responsible for the reduction of benthic biomass by as much as 70% over the last years (Denisenko 2007). As in the Canadian Arctic, the design of Ecologically or Biologically Significant Marine Areas continues in the Barents Sea.

**Kara and Laptev Seas**

In this region, few Arctic benthic time series exist and even fewer go back more than a decade or two. In the Kara Sea, infaunal community stability was evaluated for 1927–1945, 1975, 1993 and 2007 (Kozlovsky et al. 2011). The dominant species and infaunal biomass values were quite stable over time, with bivalve mollusks as the predominant taxon. The total number of species amounted to just over 200. Intense study effort has increased the number of known species in the Laptev Sea to almost 1800 (Sirenko and Vassilenko 2009), relative to 500 in an inventory from 1963. The expected number of species (an effort-independent diversity measure) in the Laptev Sea approaches the same number as in the western Barents Sea. Besides increased investigative effort, a second reason for high species richness is likely the wide range of depths in the area, ranging from shallows of the Novosibirsky Islands to the lower continental slope. It is an open question whether one should expect the same increase in species diversity if the corresponding depth range would be sampled in other Arctic areas with the same effort.

**Arctic Basin**

A recent compilation of existing literature documents 1125 taxa in the deep Arctic Basin, with the majority of taxa represented within the arthropods, foraminiferans, annelids and nematodes (Bluhm et al. 2011). Due to low overall sampling effort, this number is expected to increase with further studies of the Arctic deep sea. As known for other deep-sea basins, faunal abundance and biomass decrease with depth, but contrary to the typical mid-depth diversity peak known for other deep-sea regions, no such peak was observed in the analysis of polychaete and nematode diversity.  In contrast, modeling efforts for ostracods and foraminiferans detected mid-depth diversity peaks, but at a shallower depth than at lower latitude basins (Yasuhara et al. 2012). While several major topographically complex ridge systems bisect the Arctic Ocean basin, they do not seem to present biogeographic barriers, as the fauna in the entire basin is mostly similar to today's Atlantic fauna owing to Fram Strait being the only deep-water connection to the Arctic Ocean. At HAUSGARTEN, located in the eastern Fram Strait and the only Arctic long-term deep-sea observatory, photographic surveys conducted in 2002, 2004 and 2007 at ~2500 m depth documented significant decreases in megafauna densities, evenness and diversity measures over the study period or for the most recent sampling date (Bergmann et al. 2011). Changes in species abundances and feeding guild distribution are thought to be related to observed increases in bottom water temperatures and changes in food availability related to changes in sea ice cover.

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# 3.4 - Seabirds

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**Highlights**

- In the Atlantic Arctic, Dovekies (Little Auks), the most abundant seabird species in the arctic, show flexibility in foraging behavior and diet that has allowed some breeding colonies to do well despite warming ocean currents that affect their prey.
- Two circumpolar species, the common murre and thick-billed murre, show long-term fluctuations in population trends at colonies in response to changes in SST. These population trends tend to be synchronous within ocean basins, but alternate between Pacific and Atlantic sectors.
- Seabirds can bring beneficial nutrients from their ocean foraging grounds to breeding sites on land, but they can also concentrate and increase deposition of harmful contaminants and mercury at inland sites.

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Over the past few decades the Arctic has experienced significant warming. In the Atlantic sector there has been increase in the flow of warmer, more saline water in the West Spitsbergen Current into the Greenland Sea and into the Arctic Ocean (Piechura and Walczowski 2009). In response to these warming trends, Atlantic seabirds have shown shifts in their phenology, diets, physiology, foraging behavior and survival rates.

Dovekies (*Alle alle,* also known as the Little Auk), the most abundant seabird species in the Atlantic Arctic, and possibly in the world, are planktivores that nest on rocky slopes. During 1963 – 2008, dovekies initiated breeding 4.5 days earlier, which is likely due to earlier nest site availability because of earlier snow melt (Moe et al. 2009). In contrast, the piscivorous black–legged kittiwakes (*Rissa tridactyla*) have shown a slight trend towards later breeding, which is likely related to delays or decreases in the availability of their fish prey due to warmer sea surface temperatures (SST) and loss of sea ice (Moe et al. 2009).

In the Atlantic sector of the Arctic, copepods are a key prey in seabird food chains. With increases in the flow of the warm, Atlantic-derived water into the Greenland Sea there has been an increase in the boreal copepod, *Calanus finmarchicus*. It is smaller and has significantly lower lipid content than either of the other Arctic species of copepods (*C. glacialis* and *C. hyperboreus*) (Scott et al. 2000). Dovekies feed primarily on *C. glacialis* or *C. hyperboreus* (Karnovsky et al. 2003, 2010), but in years with high inflow of Atlantic-derived water, the proportion of *C. finmarchicus* in the food that dovekies bring back to their chicks increases (summarized in Moline et al. 2010). Overall, since 2001, there has been an order of magnitude decline in large, energy rich copepods along the eastern side of the Greenland Sea (Kwasniewski et al. 2012).

There have been several inter-colony comparisons of dovekie behavior amongst colonies that differ in the dominant prey available to foraging dovekies. Dovekies have been found to take longer foraging trips when feeding in the warmer, Atlantic-derived water, where they must feed on smaller *C. finmarchicus* (Welcker et al. 2009). Dovekies that have access to larger, high-lipid *C. hyperboreus* spend less time searching for prey and make fewer deep dives than the dovekies feeding in areas dominated by the smaller copepod species (Welcker et al. 2009).

Contrasting foraging conditions between colonies and years has been found to influence body mass and over winter survival rates of adult dovekies (Harding et al. 2011). However, despite variation in foraging conditions, dovekies have been able to maintain high reproductive success throughout the Greenland Sea (Jakubas et al. 2011, Jakubas and Wojczulanis-Jakubas *in press*, Karnovsky et al. 2003, 2010, Gremillet et al. 2012, Harding et al. 2011). Continued warming, however, could result in extinction of colonies exposed to warmer Atlantic-derived water with suboptimal prey (Karnovsky et al. 2010).

A much rarer arctic seabird that breeds in the Atlantic sector, the ivory gull (*Pagophila eburnea*), has declined by an estimated 80-90% over the past 20 years (Gilcrest and Mallory 2005). This small gull nests in isolated nunataks (rocky outcrops among glacial icefields). Because the declines appeared to be occurring throughout Canada and in different breeding habitats, Gilcrest and Mallory (2005) suggest that the causes of decline are related to factors associated with migration or over-wintering conditions. As with many Arctic seabird species, lack of monitoring makes it difficult to determine population trends or the factors influencing them (Petersen et al. 2008).

Few long-term studies exist at seabird colonies in the Pacific Arctic, with the exception of two sites monitored by the Alaska Maritime National Wildlife Refuge – the Cape Lisburne colony (mainland Alaska on the eastern Chukchi Sea) and Bluff colony (mainland Alaska in the North Bering Sea, Norton Sound). Two species have been monitored at these sites since the late 1970s, the black-legged kittiwake and the common murre (*Uria aalge*). Between 1975 and 2009, kittiwake numbers have increased overall at Cape Lisburne, but their reproductive success has declined since 2004 (Dragoo et al. 2012), which may suggest immigration to the region by prospecting birds, i.e., birds from elsewhere looking for a new place to nest. At the Bluff colony, both kittiwakes and murres have shown stable population trends, but their mean hatching dates have been earlier than the long-term (1975-2009) mean (Dragoo et al. 2012); the earlier hatch dates suggest an adaptation to earlier prey availability by both seabird species.

In the Pacific Arctic sector, vessel-based surveys have increased since 2006, due largely to an increase in physical and biological studies associated with oil and gas exploration and drilling plans. In Sigler et al. (2011), analysis of seabird distribution at sea found three major species clusters, with the north Bering Sea and Chukchi Sea birds forming one group and the central and southern Bering Sea regions another, while the Beaufort Sea birds formed a distinctly separate group. The north Bering-Chukchi region was dominated by planktivorous birds (*Aethia* auklets in the north Bering Sea and *Puffinus* shearwaters in the Chukchi Sea), whereas the Beaufort seabirds were primarily piscivorous and circumpolar in distribution.

Because the two species of murres, the common murre and thick-billed murre (*U. lomvia*) are widespread and relatively abundant throughout the Arctic, they may serve as sentinels of the arctic marine ecosystem, and have been identified as key monitoring species by the Circumplar Seabird Group of CAFF (Petersen et al. 2008). In a pan-Arctic study of both murre species, data from 32 common and 21 thick-billed murre colonies were used to examine population trends and the potential influence of SST (Irons et al. 2008). The more arctic thick-billed murre colonies increased in size when SST warmed slightly, whereas the more temperate common murre colonies increased with moderate cooling, but both species had negative trends when SST changes were extreme, regardless of direction. These patterns showed synchronous fluctuations relative to SST, with changes in trends being synchronous within ocean basins and opposite between the two basins (Pacific and Atlantic). These population trends might reflect changes in the prey base, but this remains to be determined.

Murre eggs have been key to the study of atmospheric deposition of mercury in remote areas. Isotopic composition of mercury in murre eggs (a reflection of the female bird's diet in spring) showed that the deposition increased with latitude, and was negatively correlated with sea-ice cover (Point et al. 2011). Loss of sea-ice cover could accelerate the amount of biologically accessible methylmercury throughout the food chain (Point et al. 2011). Although seabirds transport beneficial nutrients to land, Arctic seabirds may also be responsible for transporting contaminants from their ocean foraging sites to land-based colony areas. Blais et al. (2005) found that arctic ponds near large colonies of northern fulmars (*Fulmarus glacialis*) had higher levels of persistent organic pollutants and mercury. Blais et al. suggest that contaminants in seabirds could be an indicator of ecosystem health, but are also a direct concern to indigenous peoples relying on traditional foods.

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# 3.5 - Projected Impacts of Climate Change on Fish and Fisheries in the Chukchi and Beaufort Seas

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## Highlights

- Efforts to project how shifts in environmental conditions in the Arctic Ocean will affect the distribution and abundance of marine fish have yielded different outcomes depending on the region and modeling approach.
- Current prohibitions on commercial fishing in U.S. Arctic waters provide an opportunity to design a management strategy for future fisheries that is rooted in an ecosystem approach to fisheries management.
- In support of the management strategy design, the Arctic Ecosystem integrated survey (Arctic Eis) was initiated in the northern Bering Sea and Chukchi Sea in summer 2012.

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Poleward amplification of the impacts of global warming portend that Arctic (defined here as the Beaufort and Chukchi seas) marine ecosystems  will experience significant change, including loss of sea ice in summer, increased stratification and shifts in the timing and intensity of the seasonal production cycle (Slagstad et al. 2011; Wassmann et al. 2011). Several authors have attempted to project how these shifts in environmental conditions will affect the distribution and abundance of marine fish, with differing outcomes depending on the region and modeling approach (Cheung et al. 2009; Hunt Jr et al. in press; Huse and Ellingsen 2008; Mueter et al. 2011; Sigler et al. 2011). Cheung et al. (2009) projected that expanding bioclimatic windows would result in increased biodiversity in the Arctic, whereas Sigler et al. (2011), projected that the shallow sill separating the northern Bering Sea and the Chukchi Sea, and the persistent presence of the cold water over the northern Bering Sea shelf (Stabeno et al. 2012), would serve as a barrier to invasions of fish species into the region. However, Rand and Logerwell et al. (2011) reported possible range extensions for five sub-arctic fish species, including walleye Pollock (*Theragra chalcograma*), from a survey conducted in the western Beaufort Sea in 2008. Additional monitoring and research is needed to reconcile conflicting outcomes and to improve the accuracy of projected impacts of climate change on the distribution and abundance of Arctic marine fish and shellfish.

Currently, prospects for commercial fishing in the U.S. Arctic are limited by regulation  (Wilson and Ormseth 2009). For most fish stocks within the Chukchi and Beaufort Seas, stock size is insufficient to support commercial activity. For the three stocks (snow crab, *Chionoecetes opilio*; Arctic cod, *Boreogadus saida*; and saffron cod, *Englingus gracilis*) of sufficient size to support commercial activity, additional information is needed to design sustainable harvest strategies within an ecosystem context. Further, Arctic cod and saffron cod likely would remain off limits because of their ecological importance as key prey of marine mammal and seabird predators, leaving snow crab as the only likely candidate for consideration for commercial fishing. In light of this uncertainty, the North Pacific Fishery Management Council closed the region to commercial fishing for fish stocks other than Pacific salmon and Pacific halibut (Wilson and Ormseth 2009). Pacific salmon fisheries in the Arctic were already closed under a separate FMP. Pacific halibut (*Hippoglossus stenolepis*) fisheries in the Arctic were prohibited by the International Pacific Halibut Commission.

The existing prohibitions to commercial activity within the U.S. Arctic provide an opportunity to design a management strategy for future fisheries that is rooted in an ecosystem approach to fisheries management. In support of this long-term goal, NMFS (National Marine Fisheries Service) scientists are designing and implementing baseline surveys to gather information needed to develop age or length based stock assessments for fish and shellfish in the Arctic (**Fig. 3.8**). These surveys gather oceanographic measurements, abundance, stock structure, growth, food habits and bio-energetic data to identify the mechanisms underlying fish responses to changing oceanographic conditions. These measurements will enable scientists to develop an integrated ecosystem assessment (Levin et al. 2009) that will project the present and future status of marine resources under changing climate conditions as well as potential new anthropogenic stresses emerging  from increased shipping, oil and/or gas development. These ecosystem models will allow scientists to inform managers and society of the implications of different options for marine resource use in the Arctic.

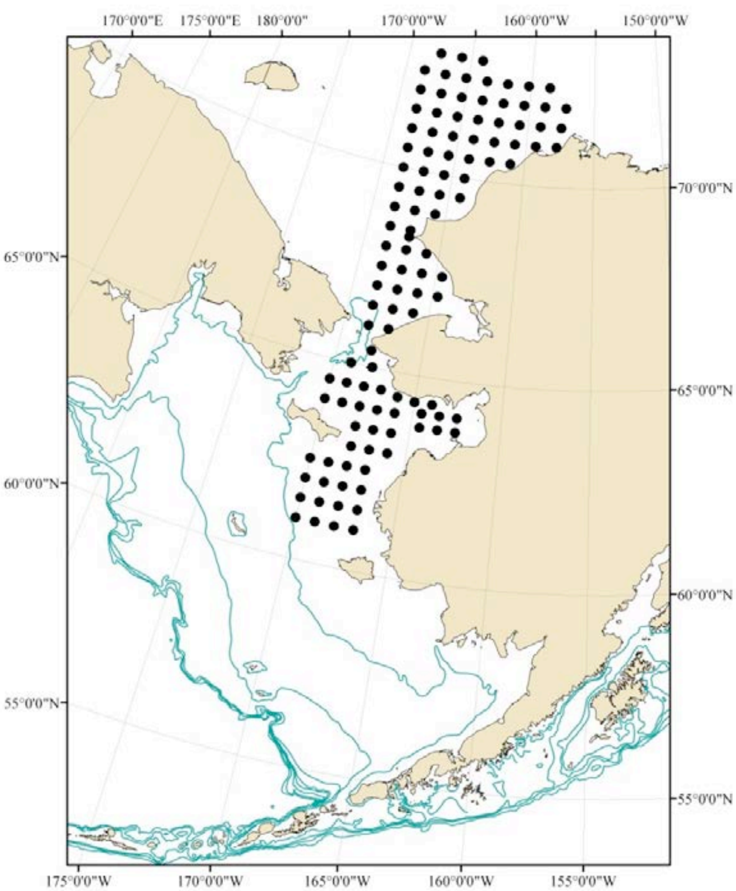

**Fig. 3.8.** Survey design for the Arctic Ecosystem integrated survey (Arctic Eis) during 2012-2013. These surveys are a collaboration between NOAA and the University of Alaska Fairbanks (UAF) to develop a greater understanding of the distribution of marine fishes and shellfishes, seabirds and the plankton they depend upon for food in the northern Bering and Chukchi Seas. The project surveys from surface to seafloor and includes diet, demography and ecosystem modeling. Collaborators include NOAA, University of Alaska Fairbanks, Bureau of Ocean Energy Management, North Slope Borough, State of Alaska and US Fish and Wildlife Service.

Recent reviews of the global status of commercial fish and fisheries reveal several factors that contribute to the achievement of sustainable fisheries (Gutierrez et al. 2011). These factors include leadership, social capital and incentives as well as a commitment to the collection and assessment of high quality information on the fished populations. It is not clear how the governance structures that contribute to sustainable fisheries will work under changing climate conditions within a multinational context (Arnason 2012). However, if at some point in the future, fish or shellfish stocks increased to a level that could sustain commercial fisheries and knowledge of the life history and population dynamics was sufficient to manage the fishery sustainably, then a comprehensive management plan would have to be developed for the region (Fluharty 2012).

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# Arctic Report Card 2012

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**Sections**

# 5. Terrestrial Cryosphere

## 5.1 - Snow

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Climate Research Division, Environment Canada

**Highlights**

- A new record low June snow cover extent (SCE) for the Northern Hemisphere (when snow cover is mainly located over the Arctic) was set in 2012. A new record low May SCE was also established over Eurasia.
- 2012 spring snow cover duration was the second shortest on record for both the North American and Eurasian sectors of the Arctic because of earlier than normal snow melt.
- The rate of loss of June snow cover extent between 1979 and 2012 (-17.6% per decade relative to the 1979-2000 mean) is greater than the loss of September sea ice extent (-13.0% per decade) over the same period.

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Snow covers the high latitude land surface for up to nine months of the year, and thereby plays a major role in the energy and freshwater budgets of the Arctic. Variability and change in snow cover extent (SCE) and snow cover duration (SCD) are of primary climatological importance, while estimates of the amount of water stored by the snowpack (snow depth or snow water equivalent) are important for hydrological purposes. While interannual variability in SCE and SCD during the snow melt period are controlled largely by surface temperature (warmer temperatures melt snow earlier), climate controls on the timing of snow cover onset in autumn and the seasonal accumulation of snow depth are more complicated, as they include influences by both temperature and precipitation. Recent reductions in Arctic spring snow cover have direct effects on many components of the Arctic physical environment, including the length of the growing season, the timing and dynamics of spring river runoff, the ground thermal regime, and wildlife population dynamics (Callaghan et al., 2012).

Northern Hemisphere spring SCE anomalies (relative to a 1988-2007 reference period) computed from the weekly NOAA snow chart Climate Data Record (CDR; maintained at Rutgers University and described in Brown and Robinson, 2011) for months when snow cover is confined largely to the Arctic showed a continued reduction from the historical mean during the 2012 spring (**Fig. 5.1**). New record lows for both May and June SCE were established over Eurasia in 2012 - the fifth consecutive year that a new record low June SCE was established for this region. Spring 2012 marked the third time in the past five years that a new record low June SCE was set for North America. The rate of snow cover loss over Northern Hemisphere land areas in June between 1979 and 2012 is -17.6% per decade (relative to the 1979-2000 mean), which exceeds the rate of September sea ice loss over the same time period (-13.0% per decade; Derksen and Brown, 2012). The rate of reduction in Arctic June SCE over the period of the NOAA data record exceeds the CMIP5 (Coupled Model Intercomparison Project Phase 5) model ensemble simulated and projected (historical + scenario rcp8.5) rate of decrease by more than a factor of three (Derksen and Brown, 2012).

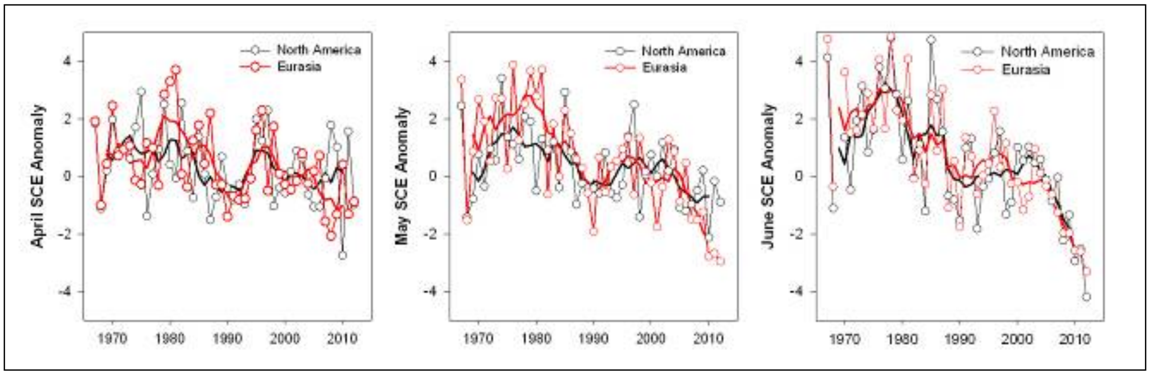


**Fig. 5.1.** Monthly Arctic snow cover extent (SCE) standardized (and thus unitless) anomaly time series (with respect to 1988-2007) from the NOAA snow chart CDR for (a) April (b) May and (c) June. Solid black and red lines depict 5-yr running means for North America and Eurasia, respectively.

Spatial patterns of fall and spring SCD departures derived from the NOAA daily IMS snow cover product for 2011/12 show no fall SCD anomalies over the Canadian Arctic, earlier than normal snow onset across the eastern Siberian Arctic, and later than normal snow onset over northern Europe (**Fig. 5.2a**). There is an almost complete absence of longer than normal SCD during the Arctic spring, with the earliest snow melt departures occurring over the central Canadian Arctic and coastal regions across the Eurasian Arctic (**Fig. 5.2b**).

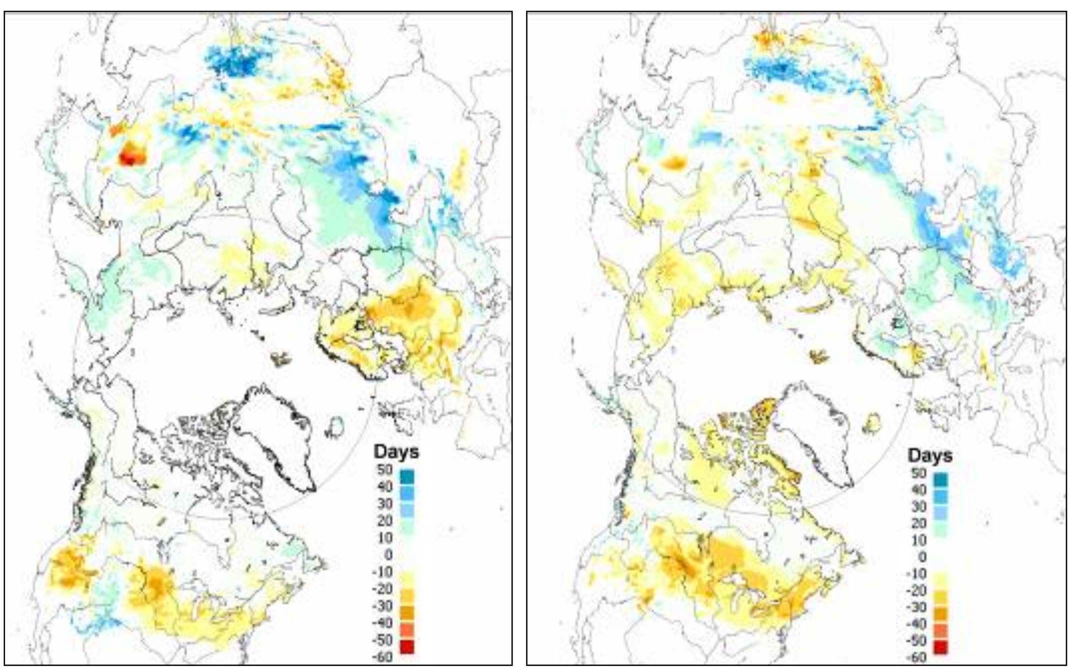

**Fig. 5.2.** Snow cover duration (SCD) departures (days; with respect to 1998-2010) from the NOAA IMS data record for the 2011-12 snow year: (a) fall; and (b) spring. Latitude circle denotes 60ºN.

Atmospheric circulation during the spring 2012 Arctic snow melt season was characterized by a strongly negative North Atlantic Oscillation (NAO) which reached a low of -2.25 in June (see also the essays on Air Temperature, Atmospheric Circulation and Clouds, and Greenland Ice Sheet). A negative NAO is associated with enhanced southerly air flow into the Arctic which contributes to warm temperature anomalies and rapid ablation of the snowpack. The only other year since 1950 to have a June NAO value lower than -2.0 was 1998, during which warm temperature anomalies were also present across Arctic land areas. The strongly negative NAO also played a key role in the extensive melting and mass losses observed in summer 2012 on the Greenland Ice Sheet (Box et al. Arctic Report Card 2012).

A striking feature in the SCD anomaly time series (also computed from the NOAA snow chart CDR using a 1988-2007 reference period) is the seasonal asymmetry of the trends through the data record (**Fig. 5.3**). In contrast to the trend towards less snow in the spring period (as a result of earlier melt), the start date of snow cover over the Arctic appears to be ~~stable during~~ the satellite era. This is surprising because the *in situ* based air temperature record (CRUtem3v, Brohan et al. 2006) identifies significant warming trends over Arctic land areas (since 1980) in both the snow onset and melt periods. The seasonal asymmetry is consistent with a weaker coupling between snow cover and air temperatures in the autumn compared to the spring. The potential impact of increased Arctic atmospheric moisture availability (Serreze et al., 2012) on Arctic snow cover (e.g. snow onset date, annual maximum SWE, snow albedo) remains to be determined.

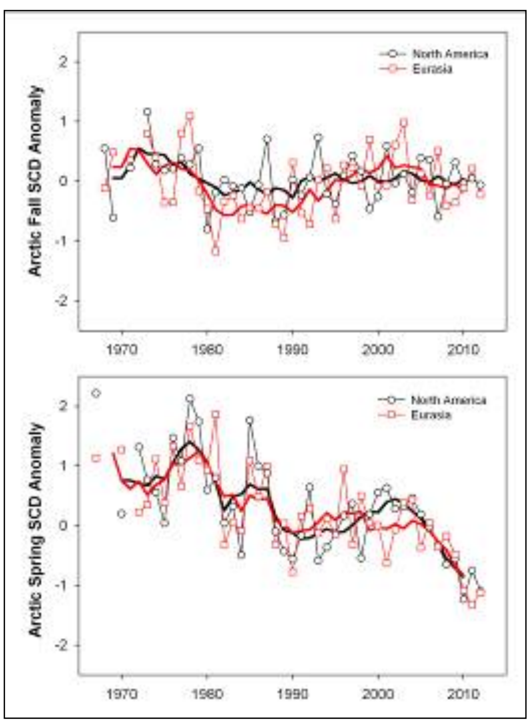

**Fig. 5.3.** Arctic seasonal snow cover duration (SCD) standardized (and thus unitless) anomaly time series (with respect to 1988-2007) from the NOAA record for (a) the first (fall) and (b) second (spring) halves of the snow season. Solid black and red lines depict 5-yr running means for North America and Eurasia, respectively.

Mean April snow depth from the Canadian Meteorological Centre (CMC) daily gridded global snow depth analysis (Brasnett, 1999) shows large regions of positive April snow depth anomalies over both the North American and Eurasian Arctic (**Fig. 5.4**). This means the record setting loss of spring snow cover in 2012 was driven more by rapid ablation rather than an anomalously low snow accumulation.

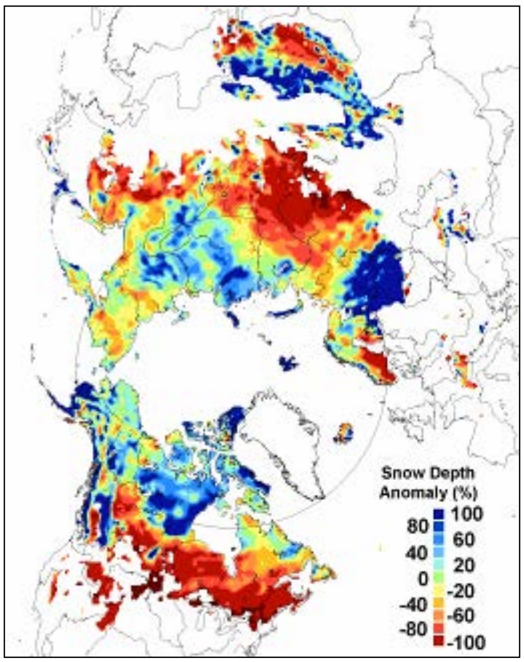


**Fig. 5.4.** April 2012 snow depth anomaly (% of 1999-2010 average) from the CMC snow depth analysis. Latitude circle denotes 60ºN.

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# 5.2 - Mountain Glaciers and Ice Caps (Outside Greenland)

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With data contribution from J. G. Cogley.

## Highlights

- In 2009-2010, the most recent balance year for which data are available for the twenty Arctic glaciers reported by the World Glacier Monitoring Service (WGMS), nineteen glaciers had a negative mass balance.
- In the 2010-2011 balance year, the mass losses from the four Canadian Arctic glaciers reported by the WGMS were the greatest in records that are between 49 and 52 years long.
- The GRACE-derived mass loss (96±49 Gt) in 2010-11 from all the glaciers and ice caps in the Canadian Arctic Islands was the largest for this region since GRACE observations began in 2002.

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Mountain glaciers and ice caps in the Arctic, with an area of over 400,000 km$^2$, contribute significantly to global sea level change (Meier et al. 2007; Gardner et al. 2011; Jacob et al., 2012). They lose mass by iceberg calving, and by surface melt and runoff. The climatic mass balance ($B_{clim}$, the difference between annual snow accumulation and runoff) is an index of how they respond to climate change and variability. Note that $B_{clim}$ is a new term (Cogley et al., 2011) synonymous with net mass balance ($B_n$) used in previous Arctic Report Cards (e.g., Sharp and Wolken, 2011)

In previous Arctic Report Cards we have reported $B_{clim}$ of 20 Arctic glaciers located in Alaska (three), Arctic Canada (four), Iceland (nine) and Svalbard (four). At the time of writing, the most recent $B_{clim}$ data for all 20 glaciers are those for the 2009-2010 balance year (**Table 4.1**). That year, all but one of the glaciers (Kongsvegen in Svalbard) had a negative annual balance. Mass balances of glaciers in Iceland were extremely negative in 2009-2010, as was that of Gulkana Glacier in interior Alaska. In the Canadian Arctic, the 2009-2010 balances of the Devon and Melville Island South ice caps were the 4$^{th}$ and 3$^{rd}$ most negative within the 51 and 49 year records, respectively (**Table 5.1** and **Fig. 5.5**).

**Table 5.1.** Measured annual net surface mass balance of glaciers in Alaska, the Canadian Arctic, Iceland and Svalbard in 2009-2010 and 2010-11. Mass balance data for glaciers in Alaska, Svalbard and Iceland are from the World Glacier Monitoring Service (2012). Those for Arctic Canada were supplied by D. Burgess and J. G. Cogley.

| **Region** | **Glacier** | **Net Balance 2009-10** (kg $m^{-2}$ $yr^{-1}$) | **Net Balance 2010-11** (kg $m^{-2}$ $yr^{-1}$) |
|---|---|---|---|
| ***Alaska*** | Wolverine | -85 | |
| | Lemon Creek | -580 | |
| | Gulkana | -1832 | |
| ***Arctic Canada*** | Devon Ice Cap | -417 | -683 |
| | Meighen Ice Cap | -387 | -1310 |
| | Melville S. Ice Cap | -939 | -1339 |
| | White | -188 | -983 |
| ***Iceland*** | Langjökull S. Dome | -3800 | |
| | Hofsjökull E | -2830 | |
| | Hofsjökull N | -2400 | |
| | Hofsjökull SW | -3490 | |
| | Köldukvislarjökull | -2870 | |
| | Tungnaarjökull | -3551 | |
| | Dyngjujökull | -1540 | |
| | Brúarjökull | -1570 | |
| | Eyjabakkajökull | -1750 | |
| ***Svalbard*** | Midre Lovenbreen | -200 | |
| | Austre Broggerbreen | -440 | |
| | Kongsvegen | +130 | |
| | Hansbreen | -14 | |

$B_{clim}$ data for 2010-2011 are only available for the four glaciers in the Canadian High Arctic (**Table 5.1**). That year, $B_n$ values were the most negative on record for all four glaciers (**Fig. 5.5**). The Canadian Arctic $B_{clim}$ records are between 49 and 52 years long, and in that time between 5 and 9 of the most negative mass balance years have occurred since 2000. The mean annual mass balance for the period 2000-2011 was between 3 (Melville South Ice Cap) and 8 (Meighen Ice Cap) times as negative as the 1963-1999 average for each ice cap. This is a result of strong summer warming over the region that began around 1987 (Gardner and Sharp 2007) and accelerated significantly after 2005

(Sharp et al. 2011). The response of $B_{clim}$ to the warming trend is clearly evident in all the mass balance records for these ice caps (**Fig. 5.5**).

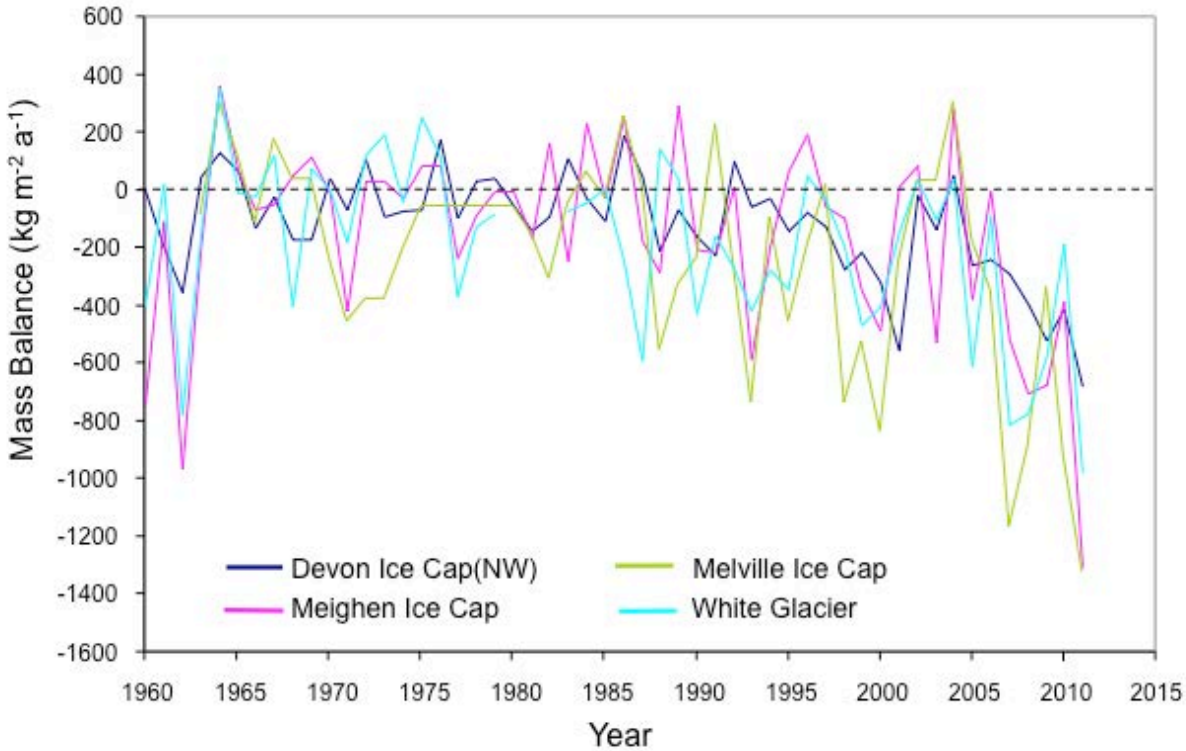


**Fig. 5.5.** Annual net surface mass balance since 1960 of four glaciers in the Queen Elizabeth Islands, Nunavut, Canada, showing the sharp acceleration in mass loss rate since 2005 and the record mass loss in 2010-11.

In 2010-11, the estimated mass loss from all the glaciers and ice caps in the Canadian Arctic Islands was -96±49 Gt (Sharp and Wolken, 2012). Derived using GRACE satellite gravimetry, this estimate of the complete mass balance, ΔM, which includes mass losses by iceberg calving, was the most negative value for this region during the GRACE observation period, 2002-2011. In the previous balance year, 2009-2010, the GRACE-derived ΔM estimate for this region was -73 ± 55 Gt, and the mean annual value for the period 2004-2009 was -63 Gt (Sharp and Wolken, 2012). The large $B_{clim}$ values reported in the previous paragraph are consistent with the increasing GRACE-derived ΔM estimates, which confirm the growing importance of glaciers and ice caps in the Canadian Arctic Islands as contributors to global sea level rise (Gardner et al. 2011).

Variability in mean summer temperature accounts for much of the inter-annual variability in $B_{clim}$ in cold, dry regions like the Canadian high Arctic while, in more maritime regions, like Iceland and southern Alaska, variability in winter precipitation is also a factor. Land surface temperature (LST) over ice in summer is likely closely related to $B_{clim}$. **Fig. 5.6** shows moderate to large LST anomalies over glaciers and ice caps throughout the Arctic, particularly in summers 2011 and 2012 in the Canadian high Arctic (northern Ellesmere, Agassiz, Axel Heiberg, Prince of Wales). More generally in

2011 (and 2012), glacier mass balance in the Canadian high Arctic was affected by the same atmospheric circulation and advection of warm air into the region that caused significant melting on the Greenland ice sheet (Sharp and Wolken, 2011; Box et al., 2011).

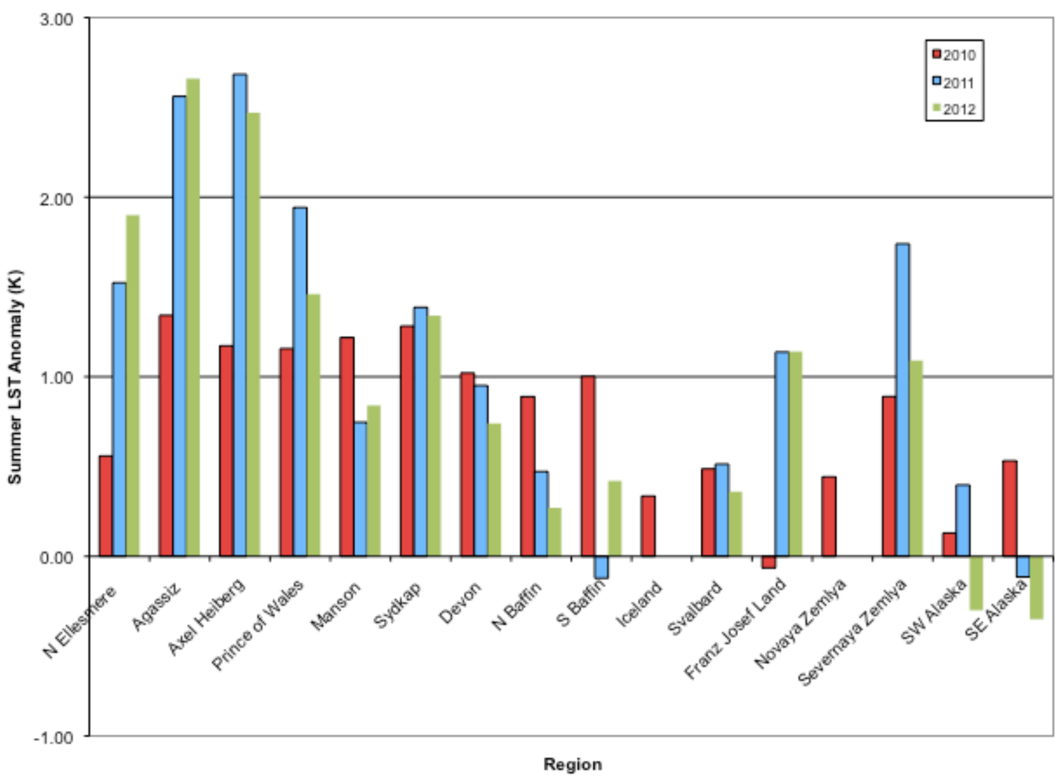


**Fig. 5.6.** Comparison of 2010, 2011 and 2012 summer mean land surface temperature (LST) anomalies (relative to 2000 to 2010 climatology) for 16 glaciated regions of the Arctic based on the MODIS MOD11A2 LST product.

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## 5.3 - Greenland Ice Sheet

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### Highlights

- The duration of melting at the surface of the ice sheet in summer 2012 was the longest since satellite observations began in 1979, and a rare, near-ice sheet-wide surface melt event was recorded by satellites for the first time.
- The lowest surface albedo observed in 13 years of satellite observations (2000-2012) was a consequence of a persistent and compounding feedback of enhanced surface melting and below normal summer snowfall.
- Field measurements at the K-Transect on the western slope of the ice sheet revealed record-setting mass losses at high elevations.
- A persistent and strong negative North Atlantic Oscillation (NAO) index caused southerly air flow into western Greenland, anomalously warm weather and the spatially and temporally extensive melting, low albedo and mass losses observed in summer 2012.

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### Surface Melting and Albedo

In 2012, ice sheet surface melting set two new, satellite era records - melt extent and melt index - according to passive microwave observations made since 1979 (e.g., Tedesco, 2007, 2009). Melt extent is the fractional area (in %) of the surface of the ice sheet where melting was detected. The melt index (MI) is the number of days on which melting occurred multiplied by the area where melting was detected.

Melt extent over the Greenland ice sheet reached record values during 11-12 July, covering as much as ~97% of the ice sheet on a single day (**Figs. 5.7 and 5.8**, and, e.g.,Nghiem et al. 2012). Confirmed by different methods for analyzing passive microwave observations (e.g., Mote and Anderson, 1995, Tedesco, 2009), the almost 100% melt extent is nearly four times greater than the ~ 25% average melt extent that occurred in 1981-2010.

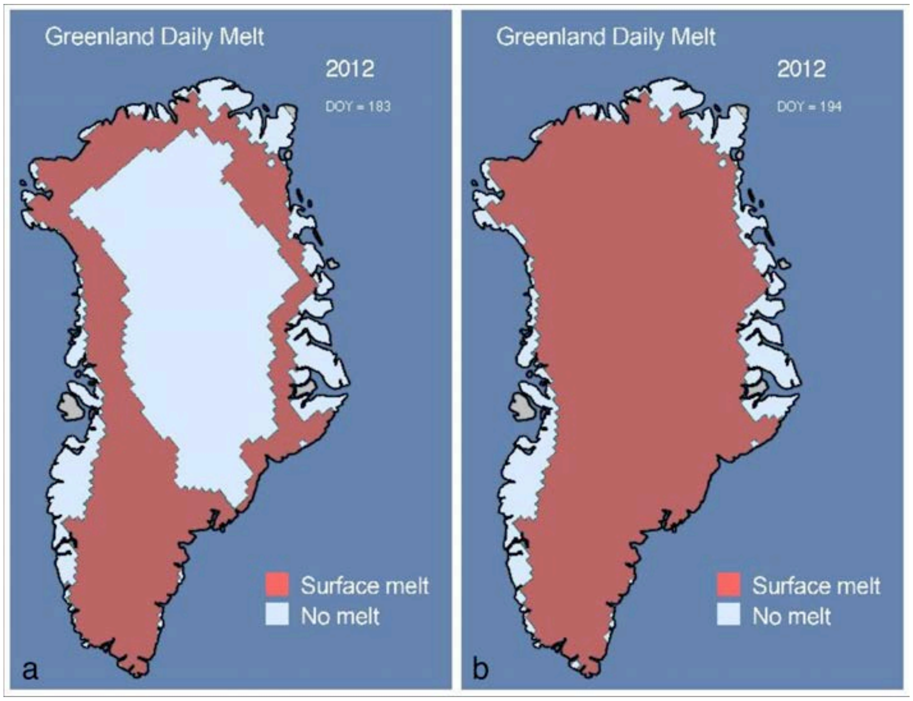


**Fig. 5.7.** Melt extent on the Greenland Ice Sheet on 1 July (a) and 12 July (b) identified by the SSM/I passive microwave sensor.

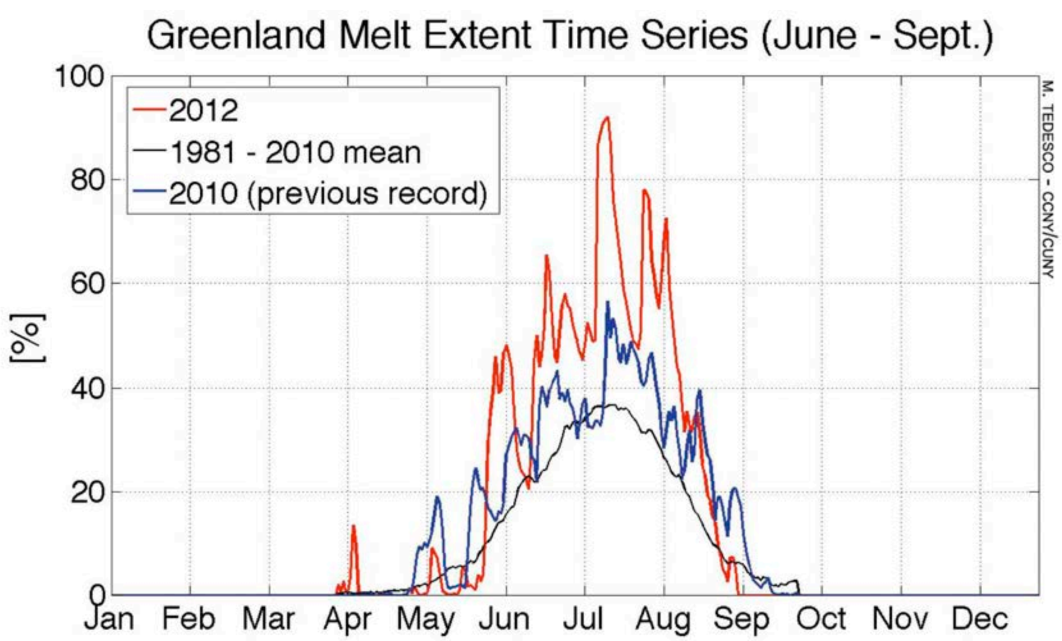


**Fig. 5.8.** Melt extent on the Greenland Ice Sheet identified by the SSM/I passive microwave sensor. The standard deviation of the 1981-2010 period is shaded.

The standardized melt index (SMI) for 2012 was ~ +2.4, almost twice the previous record of ~ +1.3 in 2010 (**Fig. 5.9**). Melting in 2012 began about two weeks earlier than average at low elevations and, for a given elevation, was sustained longer than the previous record year (2010) for most of June through mid-August. Melting lasted up to 140 days (20-40 days greater than the mean value) at low elevations in some areas of southwest Greenland. The 2012 anomaly for the number of melting days (i.e., number of melting days in 2012 minus the 1980-2010 average) exceeded 27 days in the south and 45 days in the northwest. Some areas in northwest Greenland between 1400 and 2000 m a.s.l. had nearly two months more melt than during the 1981-2010 reference period.

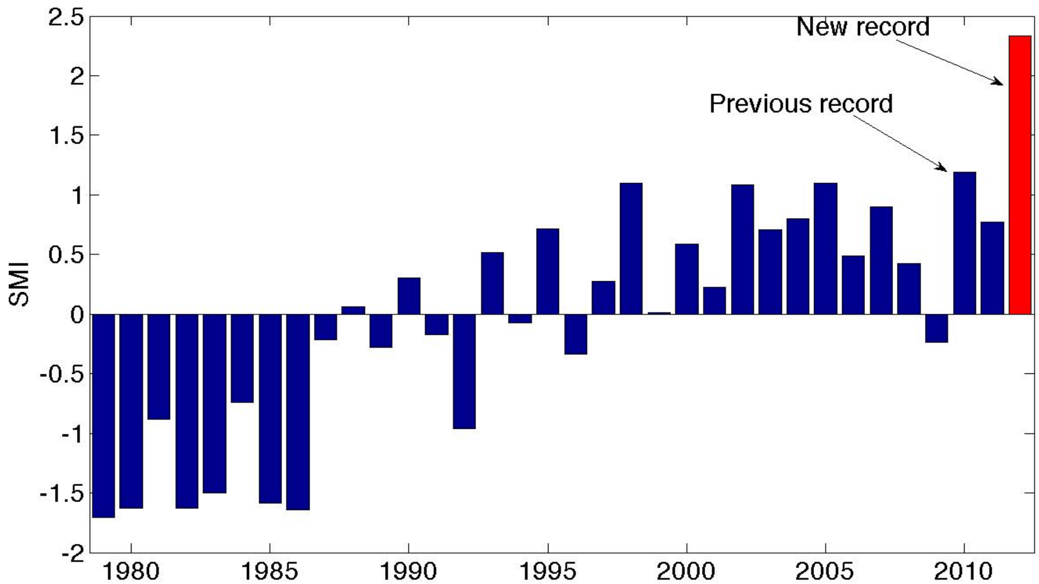


**Fig. 5.9.** Greenland ice sheet standardized melting index (SMI). The index is calculated by subtracting the melt index (MI) from the 1979 – 2012 average and dividing by its standard deviation (Tedesco 2007). MI is the number of days on which melting occurred multiplied by the area where melting was detected.

The regions of extended melt duration coincide with areas of anomalously low albedo (reflectivity). The albedo anomalies across the ice sheet in June-August 2012, when solar irradiance is highest and the albedo is lowest in magnitude, are illustrated in **Fig. 5.10**. Negative albedo anomalies were widespread across the ice sheet, but were particularly low along the western and northwestern margins in areas where darker bare ice was exposed after the previous winter's snow accumulation had melted completely away. The low albedo was compounded by a persistent feedback of enhanced surface melting due to relatively warm air temperatures and below normal summer snowfall.

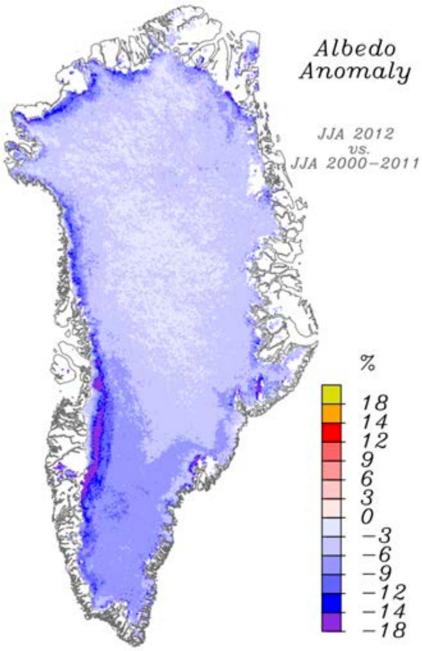


**Fig. 5.10.** Summer (JJA) albedo (reflectivity) anomaly in 2012 relative to the 2000-2011 reference period. Data were derived from MODIS (Moderate Resolution Imaging Spectroradiometer) observations.

While **Fig. 5.10** shows that there is strong spatial variation in albedo, **Fig. 5.11** shows that the area-averaged albedo of the entire ice sheet has continued to decline during the period of MODIS observations, 2000-2012. The area-averaged albedo for 2012 was a new record low, and occurred only one year after the previous record occurred.

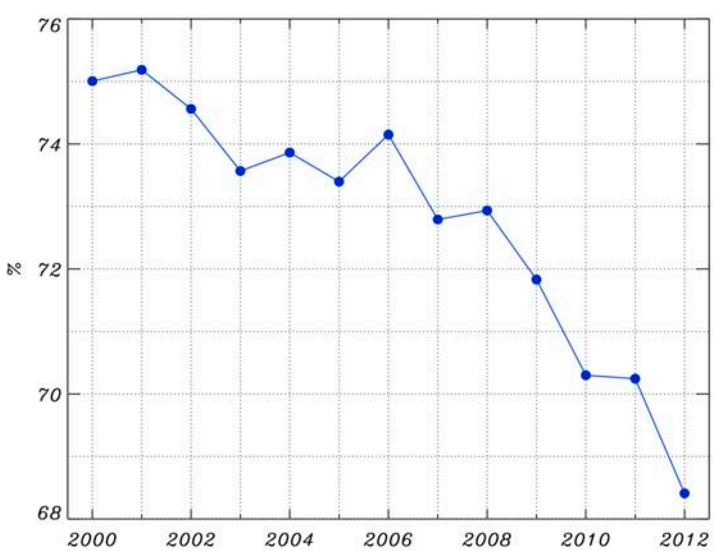


**Fig. 5.11.** Area-averaged albedo of the Greenland ice sheet during June-August each year of the period 2000-2012. Data are derived from MODIS MOD10A1 observations.

**Equilibrium Line Altitude Along the K-Transect**

The 150 km long K-Transect is located near Kangerlussuaq at 67°N between 340 m and 1500 m above sea level (a.s.l.) on the western flank of the ice sheet (van de Wal et al. 2005). The equilibrium line altitude (ELA), the highest altitude at which winter snow survives, is a convenient indicator of the competing effects of surface mass loss from melting and surface mass gain from snow accumulation. The mass balance measurements along the K-transect in 2012 corroborate the extensive surface melting observed by satellite (see the previous section on Surface Melting and Albedo).

In 2012, estimates from ground observations placed the ELA far above the height of the ice sheet topographic divide near this latitude (2687 m a.s.l.) and an unprecedented 3.7 times the standard deviation above the 21-year mean ELA value (**Fig. 5.12**). The satellite-derived snowline, a close proxy of ELA, at the end of the K-transect melt season also occurred at a record high elevation according to MODIS observations made since 2000 (**Fig. 5.12**) (Box et al. 2009a, van de Wal et al. 2012).

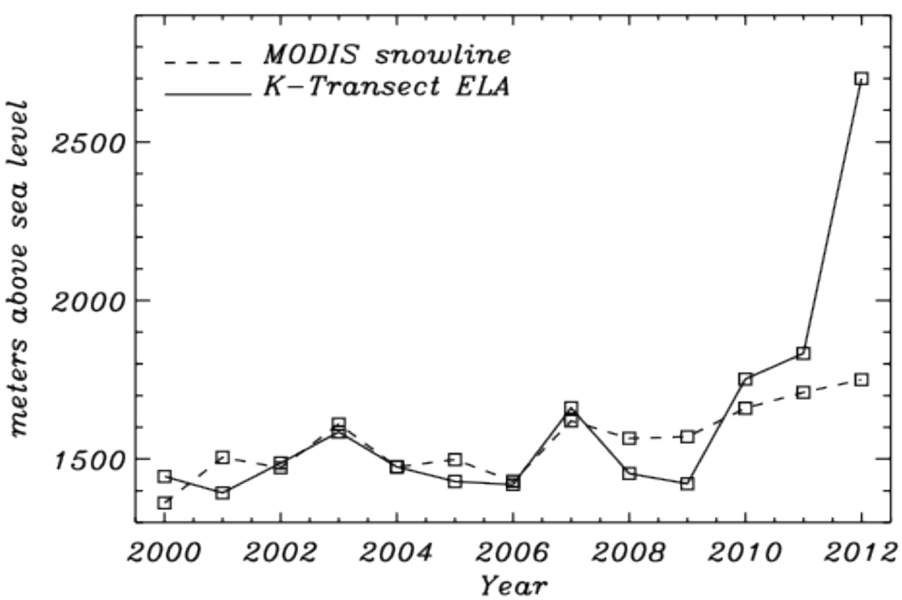


**Fig. 5.12.** The equilibrium line altitude, the highest altitude at which winter snow survives, from ground (solid line) and satellite (broken line) observations along the K-transect, located near Kangerlussuaq at 67°N between 340 m and 1500 m above sea level (a.s.l.) on the western flank of the ice sheet.

The surface mass balance, i.e., the balance between snowfall (positive mass) and melt water runoff (negative mass), during 2011-2012 along the K-transect was characterized by exceptional melt at high elevations. At the highest elevation site (S10, elevation 1847 m, almost 350 m higher than the previous ELA of 1500 m) the surface mass balance was estimated to be -74 cm w.e. (water equivalent). Relatively low winter snow accumulation at high elevation resulted in relatively low albedo, which, coupled with high air temperatures, compounded high melt rates after melt onset. Below 1500 m elevation, surface mass balance values decreased gradually to normal values near the ice margin (**Fig. 5.13**).

**Fig. 5.13** suggests that the mass balance along the transect in 2012 was the second lowest since measurements began in 1991. However, a weighted mass balance that includes the S10 site, which is above the former ELA of 1500 m, indicates that the 2011-2012 mass balance year was the most negative in 22 years.

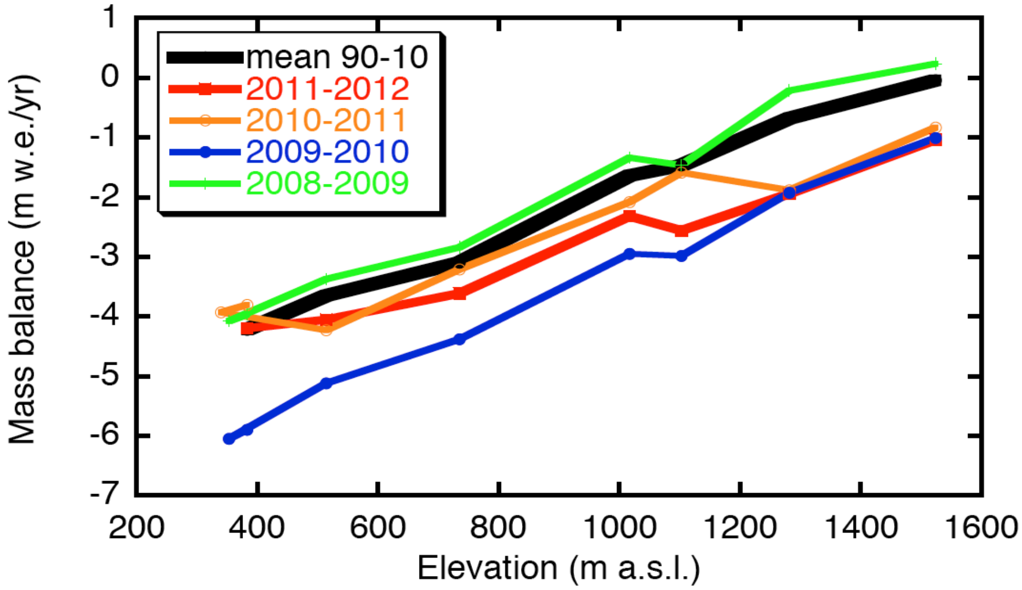


**Fig. 5.13.** Surface mass balance as a function of elevation below 1500 m along the K-transect since 2008-2009. The 20-year (1990-2010) average is also shown. The 2012 record does not include the highest elevation site, S10, which was measured for the first time in summer 2012.

**Atmospheric Circulation and Air Temperature as they Relate to Melting, Albedo and ELA**

The large melt extent and high melt index, low albedo and negative mass balance in 2012 were a consequence of the atmospheric circulation and high air temperatures.

Summer 2012 was characterized by a negative North Atlantic Oscillation (NAO) index for the entire season; a -2.4 standard deviation anomaly relative to the NAO average for June-August during 1981-2010. Consequently, sea level pressure was anomalously high over the ice sheet (see **Fig. 1.6** in the essay on *Air Temperature, Atmospheric Circulation and Clouds*) and atmospheric circulation was characterized by warm air advection from the south into western Greenland (**Fig. 5.14**). This same circulation pattern has occurred each summer since 2007 (Box et al., 2012).

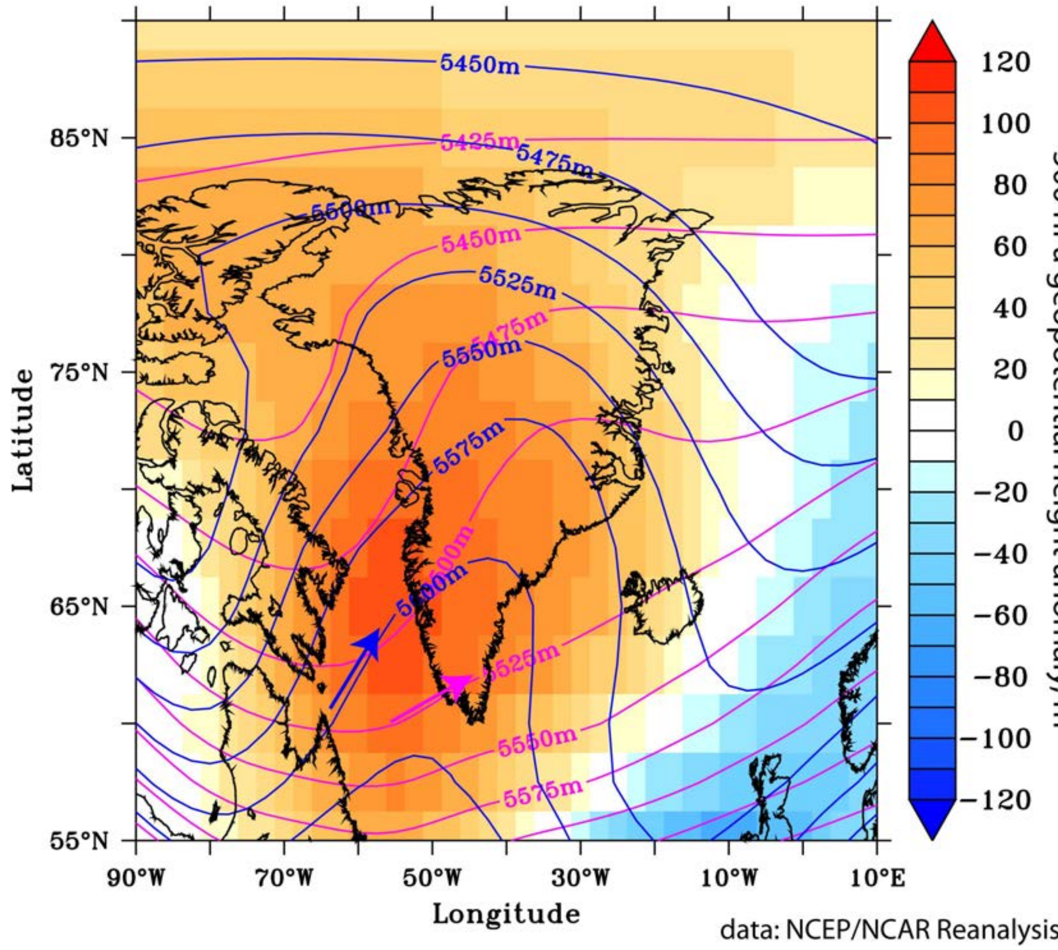


**Fig. 5.14.** Geopotential height (500 hPa) anomalies for June-August, 2012 (blue lines) referenced to the 1981-2010 mean (magenta lines). The arrow in the lower left quadrant shows that the prevailing upper air flow from the south advected warm air into Greenland. Data source: NCEP/NCAR Reanalysis version R1.

As a consequence of the atmospheric circulation pattern (**Fig. 5.14**), surface air temperatures at long-term meteorological stations in Greenland were characterized by record-setting warm summer months (not illustrated), particularly in the west and south of the island and at high elevations. For example, the Greenland Climate Network (GC-Net) automatic weather station at Summit (3199 m above sea level) measured hourly-mean air temperatures above the freezing point for the first time since measurements began in 1996 (**Fig. 5.15**). Mid-day air temperatures at Summit were around -8° C on July 10 (Julian day 191) and increased over the following 3 days to reach 0.5° C on July 12, 0.6° C on July 13, and 0.5° C on July 17, respectively. These temperatures were ~8° C above the long-term mean for the period 1996-2011.

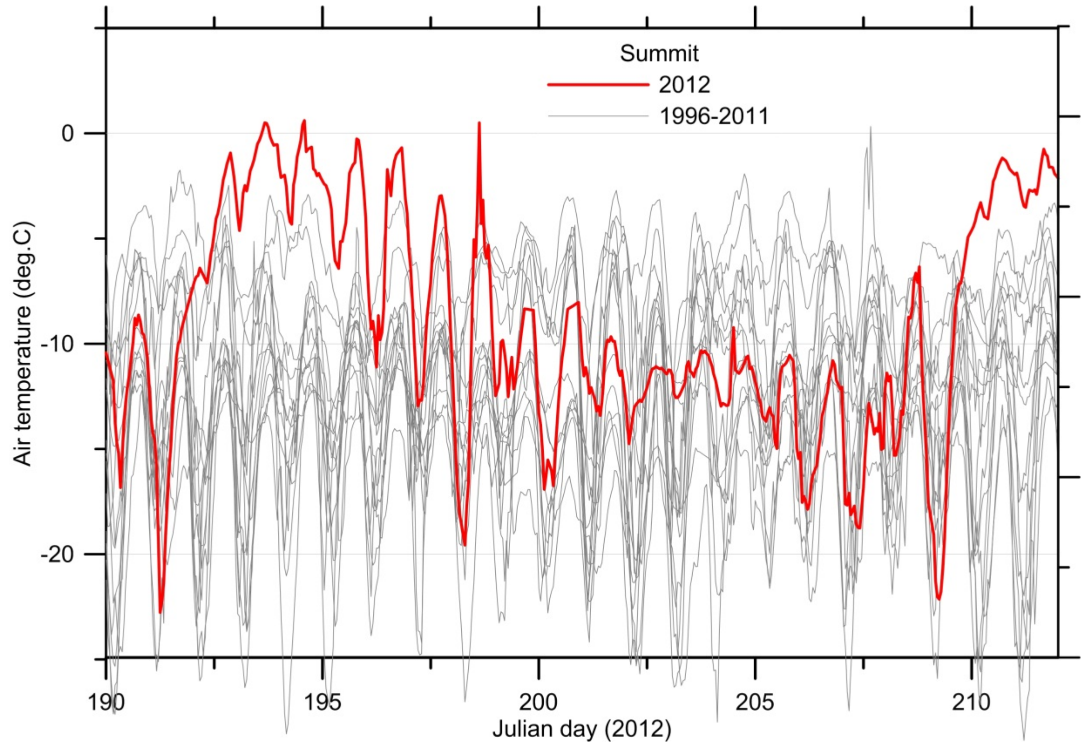


**Fig. 5.15.** Hourly mean air temperature at Summit (elevation 3199 m above sea level) from 9 July through 2 August 2012 (red) and for 1996-2011 (grey).

Seasonally-averaged upper air temperature data available from twice-daily radiosonde observations show anomalous warmth throughout the troposphere in summer 2012 (**Fig. 5.16**). Similar upper air temperature profiles were observed in 2011 (Box et al., 2011). The overall warm pattern near the surface between 850 and 1000 hPa is consistent with a warming trend evident in the period of reliable records beginning in 1964, and most pronounced since the mid-1980s (Box and Cohen 2006). This recent warming trend is seen in the long-term air temperature reconstruction for the ice sheet, which also shows that mean annual air temperatures in all seasons are now higher than they have been since 1840 (**Fig. 5.17**).

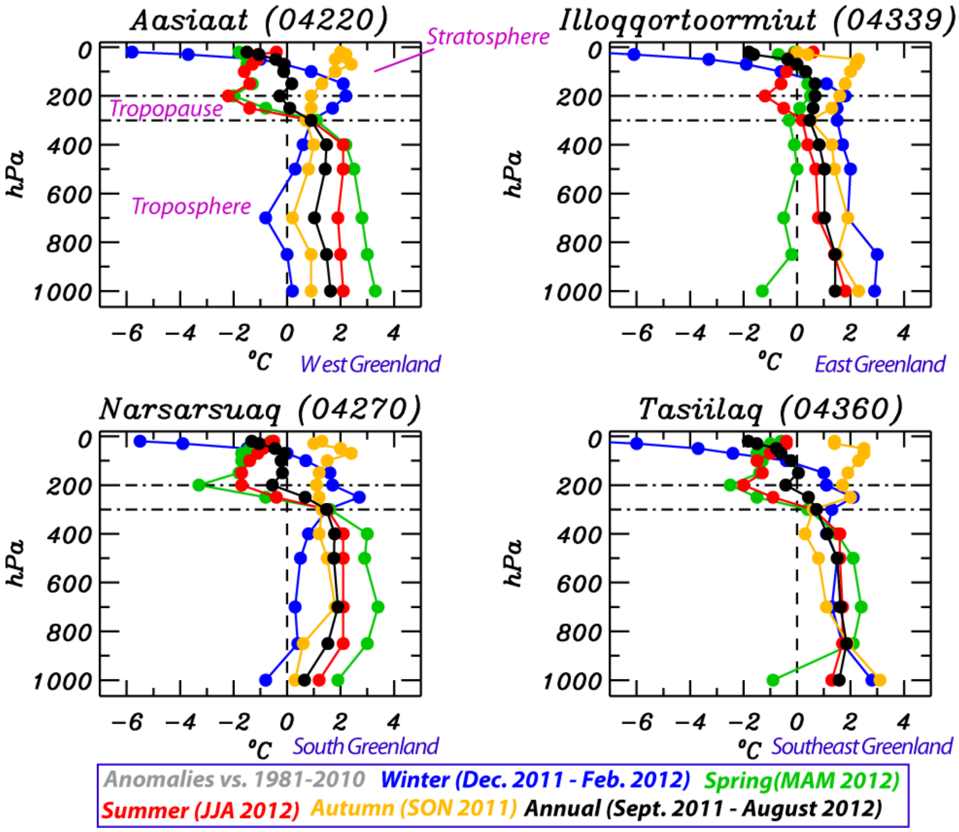


**Fig. 5.16.** Upper air temperature anomalies relative to the 1981-2010 reference period in winter, spring and summer of 2012 at four coastal locations in Greenland. The winter season includes data for December 2011.

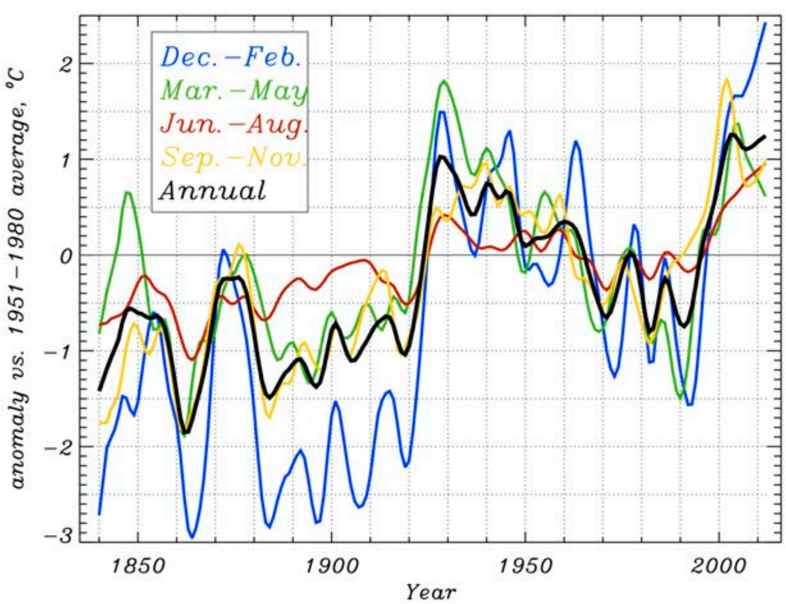


**Fig. 5.17.** Seasonally-averaged, near-surface air temperature reconstruction for the Greenland ice sheet, 1840 to August 2012 (after Box et al., 2009b)

## Greenland Mass Changes from GRACE

GRACE satellite gravity solutions computed according to Velicogna and Wahr (2006) are used to estimate monthly changes in the total mass of the Greenland ice sheet (**Fig. 5.18**). At the time of writing, data were available up until the beginning of July 2012, prior to the extensive melting that occurred later in the month. The data show that the ice sheet continues to lose mass and has contributed +7.7 mm to local sea level rise since 2002. The rate of mass loss has accelerated during the period of observation, the mass loss of 355 Gt/y in June 2008-July 2012 being almost twice that for the period June 2002-July 2006 (180 Gt/y).

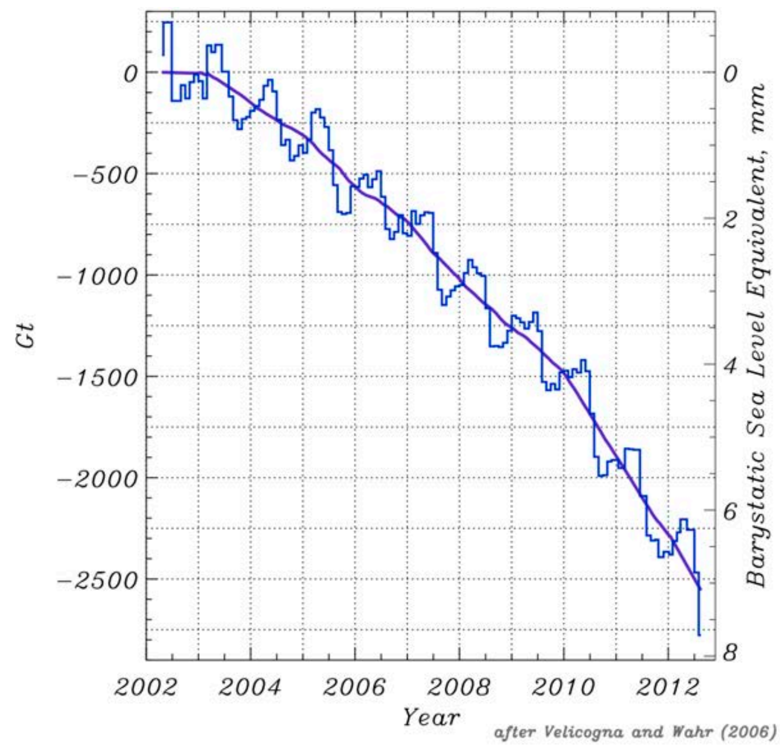


**Fig. 5.18.** Monthly smoothed (purple) and unsmoothed (blue) values of the total mass (in Gigatons, Gt), of the Greenland ice sheet from GRACE March 2002-July 2012. The barystatic ("bary" refers to weight) effect on local sea level change is the volume of freshwater added or removed divided by the ocean surface area. It does not include the effects of water thermal expansion, salinity or the associated changes to the gravity field.

## Marine-terminating Glacier Area Changes

Marine-terminating glaciers are the outlets through which the inland ice can flow most rapidly and in the largest quantities to the ocean. Iceberg calving and retreat of the glaciers leads to flow acceleration and inland ice sheet mass loss, which contributes to sea level rise.

Daily surveys using cloud-free MODIS visible imagery (Box and Decker 2011; http://bprc.osu.edu/MODIS/) indicate that in the year prior to end of the 2012 melt season the marine-terminating glaciers collectively lost an area of 297 $km^2$. This is 174 $km^2$ greater than the average annual loss rate of the previous 11 years (132 $km^2$ $yr^{-1}$) (**Fig. 5.19**) and also greater than losses in the 1980s and 1990s (Howat and Eddy 2011).

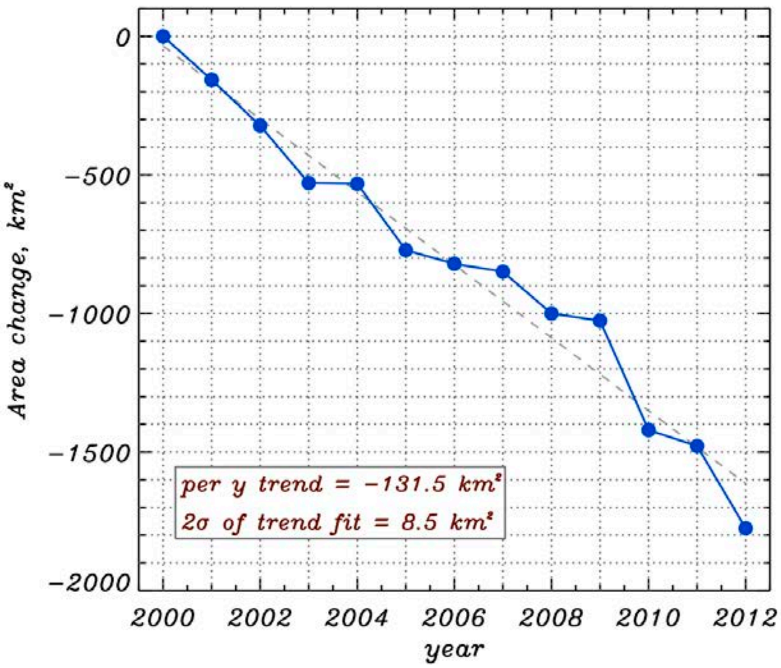


**Fig. 5.19.** Cumulative net annual area change at the 40 widest marine-terminating glaciers of the Greenland Ice Sheet (after Box and Decker, 2011). The dashed line is a least-squares regression fit with a slope of 131.5 $km^2$ of area loss per year since 2000.

Since 2000, the net area change of the forty widest marine-terminating glaciers is -1775 $km^2$ (**Fig. 5.19**), ten times the area of Washington DC. Glaciers in northernmost Greenland contributed to half of the net area change. In 2012, the six glaciers with the largest net area loss were Petermann (-141 $km^2$), 79 glacier (-27 $km^2$), Zachariae (-26 $km^2$), Steenstrup (-19 $km^2$), Steensby (-16 $km^2$, the greatest retreat since observations began in 2000) and Jakobshavn (-13 $km^2$). While the total area change was negative in 2012, four of forty glaciers did grow in area relative to the end of the 2011 melt season.

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# 5.4 - Permafrost

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**Highlights**

- In 2012, new record high temperatures at 20 m depth were measured at most permafrost observatories on the North Slope of Alaska and in the Brooks Range, where measurements began in the late 1970s. Only two coastal sites show exactly the same temperatures as in 2011.
- During the last fifteen years, active-layer thickness has increased in the Russian European North, the region north of East Siberia, Chukotka, Svalbard and Greenland.
- Active-layer thickness on the Alaskan North Slope and in the western Canadian Arctic was relatively ~~stable~~ during 1995-2011.

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The most direct indicators of permafrost stability and changes in permafrost state are the permafrost temperature and the active layer thickness (ALT). The ALT is the top layer of soil and/or rock that undergoes seasonal variation, thawing during the summer and freezing again during the fall. Permafrost temperature measured at a depth below the ALT is best to use as an indicator of long-term change. This depth varies from a few meters in warm, ice-rich permafrost to 20 m and more in cold permafrost and in bedrock (Smith et al. 2010; Romanovsky et al. 2010a). However, if continuous year-around temperature measurements are available, the mean annual ground temperature (MAGT) at any depth within the upper 15 m can be used as a proxy of the permafrost temperature. The recently concluded International Polar Year (IPY 2007-2009) resulted in significant enhancement of the permafrost observing system in the Arctic; there are now ~575 boreholes (**Fig. 5.20**; Brown et al. 2010; Romanovsky et al. 2010a). A borehole inventory, including mean annual ground temperatures for most of these boreholes, is available online (http://nsidc.org/data/g02190.html).

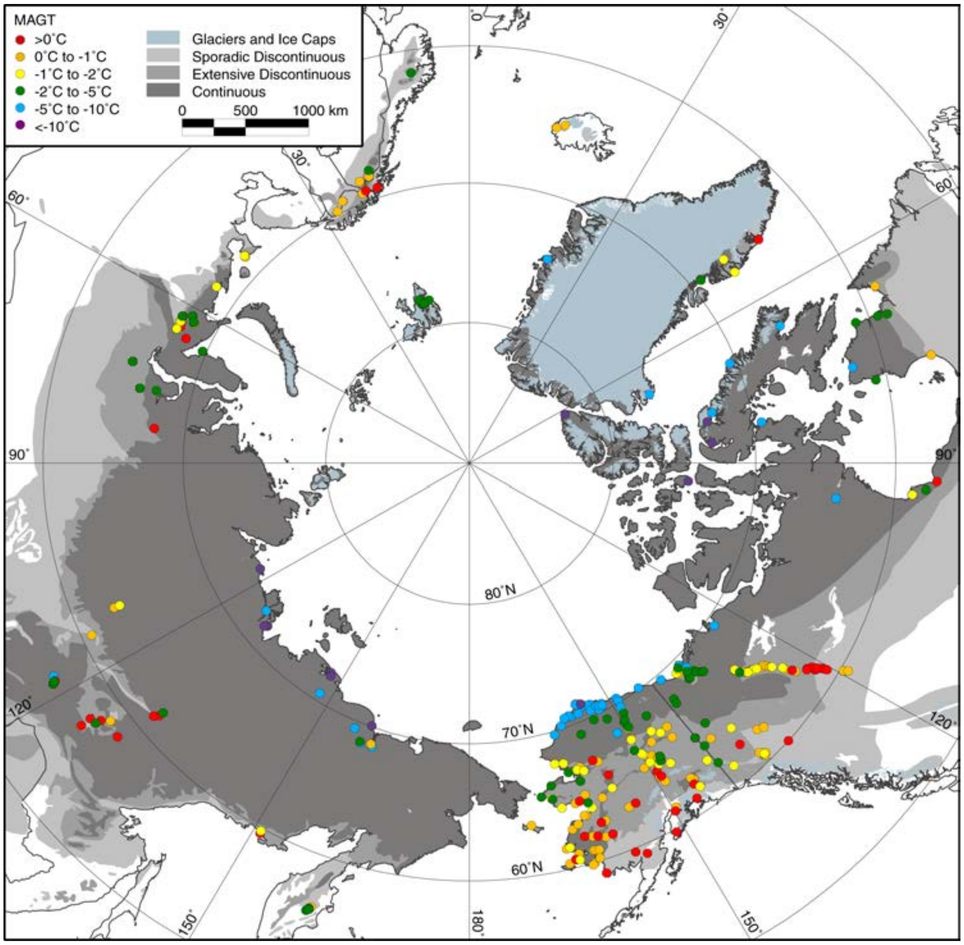


**Fig. 5.20.** Circum-Arctic view of mean annual ground temperature (MAGT) in permafrost during the International Polar Year (2007-2009; from Romanovsky et al. 2010).

Permafrost temperatures in the Arctic and sub-Arctic lowlands generally follow a latitudinal gradient, decreasing northward. Higher ground temperatures are found in the southern discontinuous zone, where MAGT is above 0°C at many locations (**Fig. 1**). The temperature of warm permafrost in the discontinuous zone generally falls within a narrow range, with MAGT at most sites being > -2°C (Christiansen et al. 2010; Romanovsky et al. 2010a; Smith et al. 2010) (**Fig. 5.20**). Temperatures as low as -3°C or even -4°C, however, may be observed in some specific ecological or topographic conditions (Jorgenson et al. 2010). A greater range in MAGT occurs within the continuous permafrost zone, from >-1°C at some locations to as low as -15°C at others (Christiansen et al. 2010; Romanovsky et al. 2010a; Romanovsky et al. 2010b; Smith et al. 2010). MAGT > 0°C is observed at some locations near the southern boundary of the continuous zone (Fig. 1), which may indicate that this boundary is shifting northward (Romanovsky et al. 2010b). Permafrost temperatures <-10°C are presently found only in the Canadian Arctic Archipelago (Smith et al. 2010) and near the Arctic coast in Siberia.

Our understanding of the thermal state of mountain permafrost in northwestern Canada has improved in recent years (e.g. Lewkowicz et al. 2012). In the sporadic permafrost zone of the southern Yukon, warm, thin permafrost formed under colder conditions continues to persist in organic soils (Lewkowicz et al. 2011). Recent research has also indicated that air temperature inversions are an important factor influencing mountain permafrost distribution (Lewkowicz and Bonnaventure 2011, Lewkowicz et al. 2012). Thus, permafrost may be less extensive at higher elevations than predictions based on air temperatures measured at standard weather stations located in valley floors (Smith et al. 2010).

Systematic observations of permafrost temperature in Alaska, Canada and Russia since the middle of the 20th Century provide several decades of continuous data from several sites. The data allow assessment of changes in permafrost temperatures on a decadal time scale. A general increase in permafrost temperatures is observed during the last several decades in Alaska (Romanovsky et al. 2007; Osterkamp 2008; Smith et al. 2010; Romanovsky et al. 2010a), northwest Canada (Smith et al. 2010) and Siberia (Oberman 2008; Romanovsky et al. 2010b). At most Alaskan permafrost observatories there was substantial warming during the 1980s and especially in the 1990s (**Fig. 5.21**). The magnitude and nature of the warming varies between locations, but is typically from 0.5°C to 2°C at the depth of zero seasonal temperature variations over this 20 year period (Osterkamp 2008). However, at the beginning of the 2000s, permafrost temperature was relatively stable on the North Slope of Alaska (Smith et al. 2010) (**Fig. 5.21**), and there was even a slight decrease (from 0.1°C to 0.3°C) in Interior Alaska during the last four years (**Fig. 5.21**). However, since 2007 the permafrost warming has resumed. This warming trend is initially evident at the Arctic coastal sites and then propagates into the Brooks Range northern foothills (**Fig. 5.21**), where a noticeable warming in the upper 20 m of permafrost has become evident since 2008 (Romanovsky et al. 2011).

In 2012, new record high temperatures at 20 m depth were measured at most permafrost observatories on the North Slope of Alaska, where measurements began in the late 1970s (**Fig. 5.21**). Only sites at West Dock and Deadhorse showed exactly the same record-high temperatures observed in 2011. Record high temperatures were also observed in 2012 in the Brooks Range (Chandalar Shelf) and in its southern foothills (Coldfoot). These distinct patterns of permafrost warming on the North Slope and a slight cooling in the Alaska Interior are in good agreement with the air temperature patterns between the Arctic and the sub-Arctic described in the essay on *Air Temperature, Atmospheric Circulation and Clouds*. These permafrost temperature patterns may also be a result of snow distribution variations (see the *Snow* essay for more information on changing snow cover).

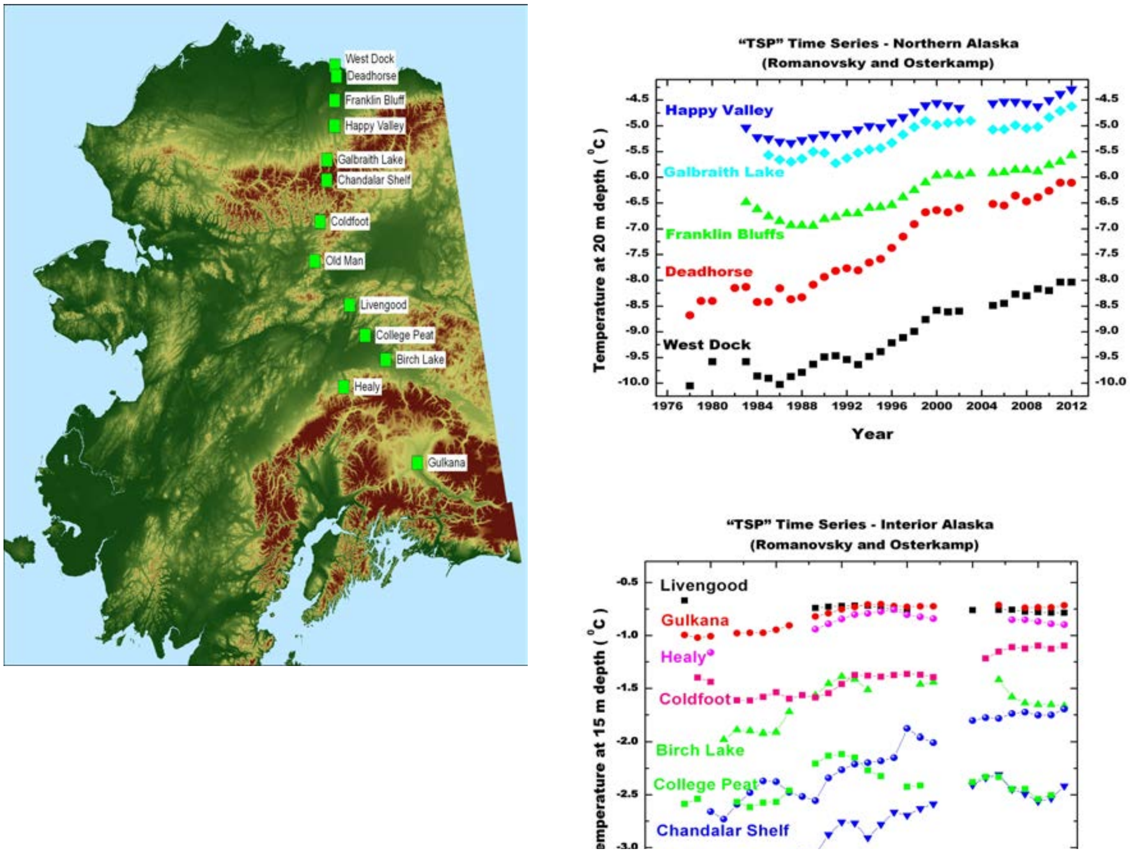


**Fig. 5.21.** Time series of annual permafrost temperatures (right) measured from north to south across Alaska (left) in the continuous and discontinuous permafrost zones.

A similar permafrost temperature increase during the last 40 years was estimated for colder permafrost in north-west Canada (Burn and Kokelj 2009). In the discontinuous zone of western Canada, the increase in permafrost temperature continues to be small, e.g., not exceeding 0.2°C per decade in the central and southern Mackenzie Valley (Fig. **5.22a**) (Smith et al. 2010, Derksen et al. 2012). In the eastern and high Canadian Arctic, greater warming has been observed, and since 2000 there continues to be a steady increase in permafrost temperature (**Fig. 5.22b**). Significant increases in winter air temperature appear to be largely responsible for the recent increases in permafrost temperature in northern Canada, particularly at polar desert sites where snow cover is minimal (Smith et al. 2012). These changes in permafrost conditions are consistent with the recent observed reduction in spatial extent and mass of the cryosphere across the Canadian Arctic (Derksen et al. 2012).

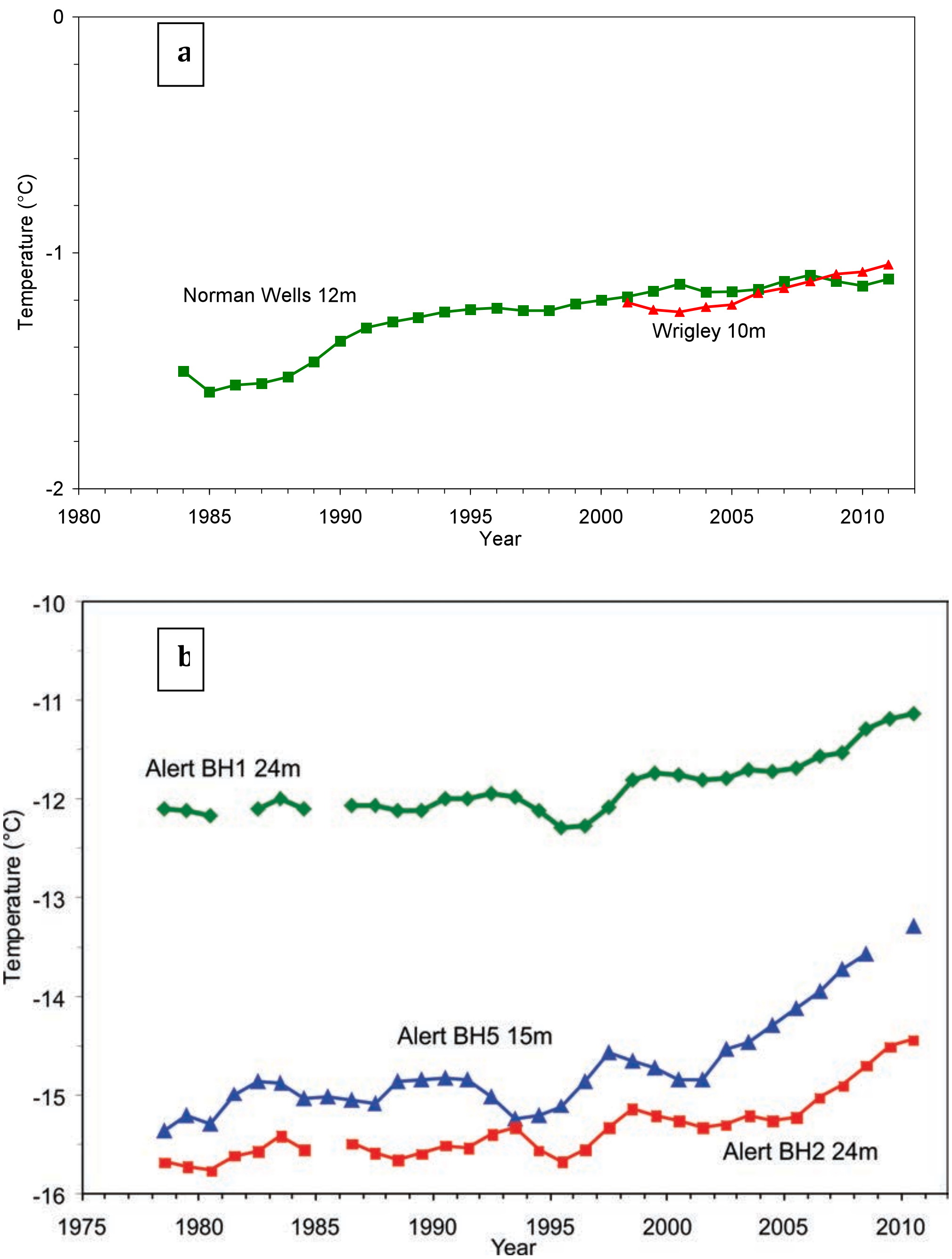


**Fig. 5.22.** Time series of mean annual permafrost temperatures at (top) 12 m depth at two sites in the discontinuous permafrost zone of the central Mackenzie Valley, Northwest Territories, Canada and (bottom) 15 m and 24 m depth at Alert, Nunavut, Canada (updated from Smith et al. 2010, 2012). The method described in Smith et al. (2012) was used to address gaps in the data record and produce a standardized record of mean annual ground temperature. Note the large temperature difference between the low (a) and high (b) latitude sites.

Permafrost temperature has increased by 1°C to 2°C in northern Russia during the last 30 to 35 years (Oberman, 2008; Romanovsky et al. 2010b). An especially noticeable temperature increase was observed during the late 2000s in the Russian Arctic, where the mean annual temperature at 15 m depth increased by >0.35°C in the Tiksi area and by 0.3°C at 10 m depth in the European North of Russia during 2006-2009. However, relatively low air temperatures during summer 2009 and the following winter of 2009-2010 interrupted this warming trend at many locations in the Russian Arctic, especially in the western sector. Nevertheless, many sites in East Siberia show continuous increase in permafrost temperatures at 15 to 25 m depth (**Fig. 5.23**).

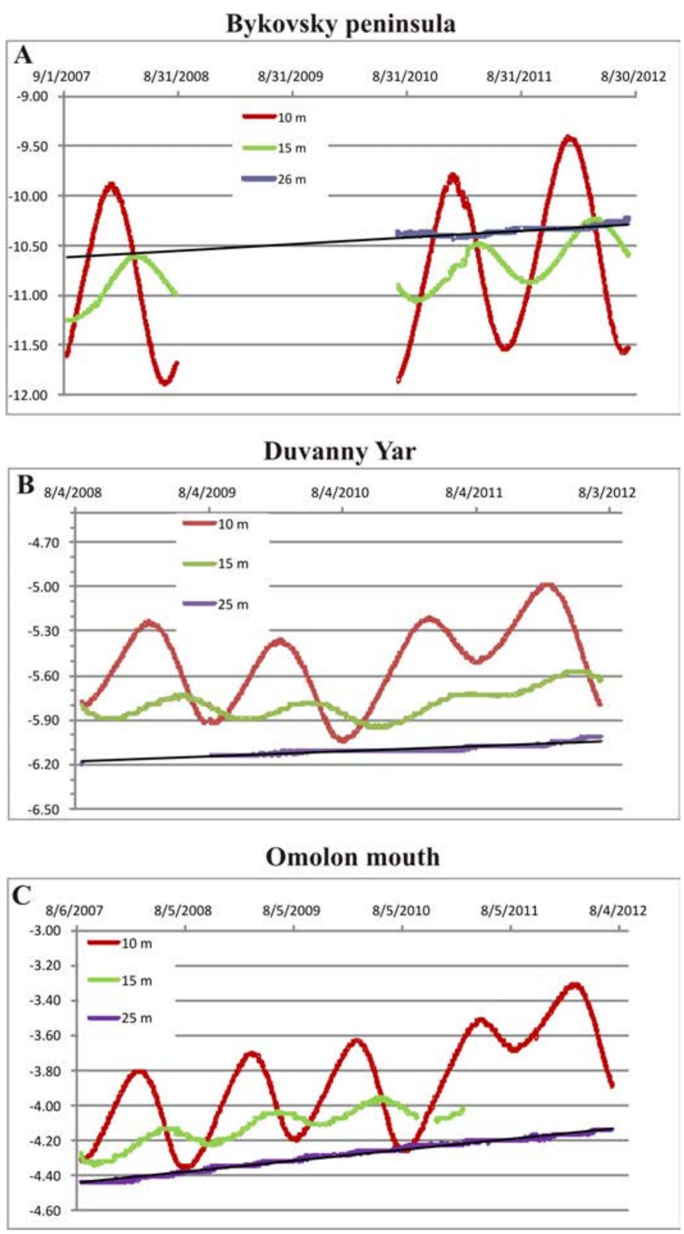


**Fig. 5.23.** Time series of permafrost temperatures at observation sites located in tundra (a) and boreal forest (b and c) eco-zones in East Siberia.

A common feature at Alaskan, Canadian and Russian sites is greater warming in relatively cold permafrost than in warm permafrost in the same geographical area (Romanovsky et al. 2010a). This difference in the rate of warming is responsible for the fact that permafrost temperatures at such distant sites in Alaska as Chandalar Shelf in the Brooks Range and Birch Lake in Interior Alaska now have exactly the same permafrost temperatures. Another such example is the Old Man and College Peat sites (**Fig. 5.21**)

Unlike the rest of the Northern Hemisphere, the Nordic area, including Greenland, does not have comparable long-term permafrost temperature data. A network of monitoring sites was, however, established during the IPY (Christiansen et al., 2010). Some of few sustained permafrost monitoring sites have significantly shorter records that begin at the end of the 1990s. However, these also show a recent decadal warming of 0.04 to 0.07ºC/yr in the highlands of southern Norway, northern Sweden and Svalbard, with the largest warming in Svalbard and in northern Scandinavia (Isaksen et al. 2007; Isaksen et al, 2011; Christiansen et al. 2010).

Long-term observations of the changes in active-layer thickness (ALT) are less conclusive. Thaw depth observations exhibit substantial inter-annual fluctuations, primarily in response to variations in summer air temperature (e.g. Smith et al. 2009; Popova and Shmakin, 2009). Decadal trends in ALT vary by region. (Shiklomanov et al., 2012).

A progressive increase in ALT has been observed in some Nordic countries, e.g., in the Abisko area of Sweden since the 1970s, with an accelerated rate after 1995 that resulted in disappearance of permafrost in several mire landscapes (e.g. Åkerman and Johansson 2008, Callaghan et al. 2010). This increase in thaw propagation ceased during 2007-2010, coincident with drier summer conditions (Christiansen et al. 2010). Increases in ALT since the late 1990s have been observed on Svalbard and Greenland, but these are not spatially and temporarily uniform (Christiansen et al. 2010).

Increase in ALT during the last fifteen years has been observed in the north of European (Drozdov et al. 2012; Kaverin et al, 2012), in the north of East Siberia (Fyodorov-Davydov et al. 2008), and in Chukotka (Zamolodchikov, 2008), but ALT was relatively stable in northern regions of West Siberia (Fig. 5).

Active-layer trends are different for North American sites, where a progressive increase of ALT is evident only at sites in Interior Alaska; there, the maximum ALT for the 18-year observation period occurred in 2007 (**Fig. 5.24**). Active-layer thickness on the North Slope of Alaska is relatively stable, without pronounced trends during 1995-2008 (Streletskiy et al. 2008: Shiklomanov et al. 2010). Similar results are reported from the Western Canadian Arctic. Smith et al. (2009) found no definite trend in the Mackenzie Valley during the last 15 years, with some decrease in ALT following a maximum in 1998. Although **an** 8 cm increase in thaw depth was observed between 1983 and 2008 in the northern Mackenzie region, shallower thaw has been observed **since** 1998 (Burn and Kokelj 2009). In the eastern Canadian Arctic, ALT increased since the mid-1990s, with the largest increase occurring in bedrock of the discontinuous permafrost zone (Smith et al. 2010).

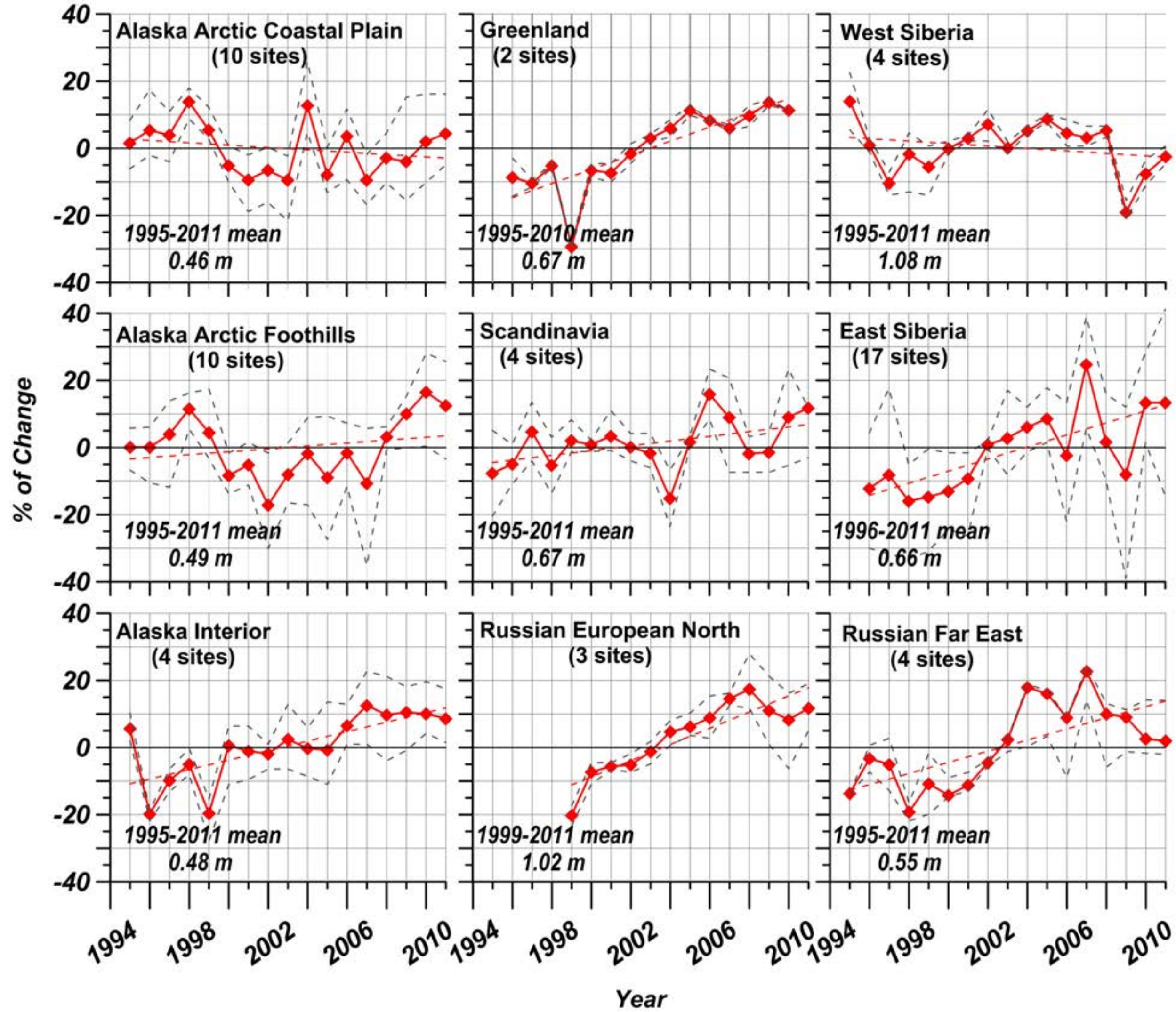


**Fig. 5.24.** Active-layer change in nine different Arctic regions according to the Circumpolar Active Layer Monitoring (CALM) program. The data are presented as annual percentage deviations from the mean value for the period of observations (indicated in each graph). Mean, minimum and maximum thaw depth observations from the end of the thawing season were used to evaluate long-term trends. Availability of at least ten years of continuous thaw depth observations through to the 2011 thawing season was the only criterion for site selection. For Greenland sites, 2011 data are not available. The number of CALM sites within each region varies and is indicated in each graph.

The last 30 years of ground warming have resulted in the thawing of permafrost in areas of discontinuous permafrost in Russia (Oberman 2008; Romanovsky et al. 2010b). This is evidenced by changes in the depth and number of taliks (a sub-surface layer of year-round unfrozen ground within permafrost), especially in sandy and sandy loam sediments compared to clay. A massive development of new closed taliks in the southern continuous permafrost zone, resulting from increased snow cover and warming permafrost, was responsible for the observed northward movement of the boundary between continuous and discontinuous permafrost by several tens of kilometers (Oberman and Shesler 2009; Romanovsky et al. 2010b). The frequently-reported long-term permafrost thawing in the Central Yakutian area around the city of Yakutsk are directly related to natural (forest fire) or anthropogenic (agricultural activities, construction sites) disturbances (Fedorov and Konstantinov 2008) and are not significantly correlated with climate (Romanovsky et al. 2010b).

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## Review of Arctic Report Card 2012

Reviewer 2

**Section 3. Marine Ecosystem**

**3.2 Cetaceans and Pinnipeds (Whales and Seals)**
In general, I find this section very weak and void of some important and relevant new data. In particular, that associated with ringed seals. I would strongly suggest including some of findings and conclusions from the following fairly recent publications;

A new sub-section on ringed seals has been added; it includes some of the references recommended below.


Chambellant, M, I Stirling, SH Ferguson. **2012**. Temporal variation in western Hudson Bay ringed seal (*Phoca hispida*) diet in relation to environment. Marine Ecology Progress Series in press.

Gaden, A.; Ferguson, S.H.; Harwood, L.; Melling, H.:, Stern, G.A. **2009**. Mercury trends in ringed seals (*Phoca hispida*) from the western Canadian Arctic since 1973: Associations with sea ice duration. Environmental Science & Technology 43, 3646–3651.

Gaden, A, Ferguson S, Harwood L, Melling H, Alikamik J, Stern G. **2012**. Western Canadian Arctic ringed seal organochlorine contaminant trends in relation to sea ice break-up. Environmental Science & Technology. 46, 4427−4433.

Chambellant, M, I Stirling, WA Gough, SH Ferguson. **2012**. Temporal variations in Hudson Bay ringed seal (*Phoca hispida*) life-history parameters in relation to environment. Journal of Mammalogy 93: 267-281.

Chambellant, M, NJ Lunn, SH Ferguson. **2012**. Temporal variation in distribution and density of ice-obligated seals in western Hudson Bay, Canada. Polar Biology on line. DOI 10.1007/s00300-012-1159-6


Other comments
Title; The text is not simply restricted to whales and seals. Mention is made of "core" Arctic animals etc and walrus and polar bear are included in Table 3.1. A more appropriate or representative title should be considered. The title has been changed to 'Marine Mammals' to reflect the broader scope.

Highlights
Either use a mathematical numeral system (a number) or a numeral linguistics system (a word), not both. All numbers are now given as words.

The highlighted points are not very informative. Why is it important to note that bowhead whales are singing continuously through the winter? Has this changed from previous years?? Use perhaps "In Hudson Bay, later departures of beluga from there summering grounds have been linked to warmer and more spatially more heterogeneous sea temperatures” It is now noted that Spitzbergen bowhead whales are critically endangered; hence the importance of their winter singing. The Hudson Bay highlight has been added.

Line 1278. Should “or” be “and”? No. “and” is correct.

**3.3 Arctic Benthos**

Line 1450; Delete “from”. Should be (Grebmeier, 2012) This was corrected before the review was received.
Line 1464’ delete “the”. Should be “….Chukchi Sea, it becomes….” This has been corrected.
Lines 1514-515; Should be “…differ among the seven regions on the Canadian Arctic shelf with taxonomic diversity higher in the eastern regions relative to the central and western Archipelago. This was corrected before the review was received.
Lines 1517-1518; Should be “….992 taxa, and is similar to the more highly sampled Atlantic…..” This has been corrected.
Line 1532; remove “mostly” This has been corrected.
Lines 1534-1535; Should be “….as a consequence of climate change, ongoing oil and mineral exploration, and a …..” This has been corrected.

**3.4 Seabirds**

Highlights, line 1689; define SST This has been corrected.
Lines 1703-1704; Should the sentence read ”over the 45 year period from 1963-2008” or perhaps “sometime over the 45 year period from 1963-2008”? This has been clarified. It now reads “From 1963 to 2008, dovekies …..”.

**3.5 Projected Impacts of Climate Change on Fish and Fisheries in the Chukchi and Beaufort Seas.**

Lines 1915-1925; Aside from the future NMFS studies there has been some significant Canadian studies on going in the Beaufort Sea. In particular those funded by BREA, the Beaufort Regional Environmental Assessment program. The first field programs for these studies were completed in October 2012. Both were highly successful (see project descriptions below).

http://www.beaufortrea.ca/research/active-acoustic-mapping-of-fish-in-the-beaufort-sea/

http://www.beaufortrea.ca/research/impacts-of-development-in-the-beaufort-sea-on-fish-their-habitats-and-ecosystems/

We thank the reviewer for drawing attention to these studies. A brief note and references have been added to the essay.

**Section 4. Terrestrial Ecosystem**

**4.1 Vegetation**

Lines 2132-2133; Should be "….season (SOS) began earlier while the end of the growing season (EOS)….." This has been corrected.

**4.2 Lemmings**
Line 2618; Should be "…Around 2000, the population…" This was corrected before the review was received.

**4.3 Arctic Fox**
In the Highlights, Point 1. add "current populations are estimated to be less than 200 individuals and compare to over 15000 individuals during the mid-19th century" the end of the last sentence. The change in fox numbers has been added as a highlight in its own right.

Line 2776; Comment. According to the information in section 4.2, the **regularity** in the cycle is not as evident. Might be worth making a comment. The text has been modified slightly to say that lemming fluctuation normally have a regularity.

Line 2787-2788; "Present low numbers of the predators in some areas [REF] may…" Reference to Angerbjörn et al. has been added to the text and the reference list.

Line 2810; Change to "The Artic fox has developed many physical attributes that have allowed them to adapt to the Arctic environment…." The sentence has been modified as proposed.

**4.4 – Caribou and Reindeer**
Line 3040; Change to "…summer aggregations, but did not include the use of …… The sentence has been modified as proposed.

Line 3070; Change to "…estimates after 1994 were limited in number for the Ahiak (9) and Beverly herds (10). The Beverly herd likely peaked……" The sentence has been modified as proposed.

Line 3089; Change "followed" to "following" This has been corrected.

Lines 3095-3096; Delete "Since the mid-1980s, the George River herd (14) declined sharply.Add "The George River herd (14) increased from 5000 animals……" This change has been made as proposed.

Line 3120; Delete "in 1975" This change has been made as proposed.

Line 3121; When was the herd count at 600,000 animals? The sentence previously said up to 450,000. The dates have been clarified and the herd size has been corrected to 625,000.

Line 3123; Change to "…although a more recent estimate has not…" The sentence has been modified and improved.

Line 3124; Delete “since 2000” This change has not been made. With the modification/improvement made as described in the previous request, it is better to keep ‘in 2000”.

Reviewer 3

GENERAL COMMENTS

1.The reports made available to me are of variable quality and legibility. Some are phrased in a nice, consistent way, others are loaded with technical jargon and accornyms that they cannot be followed easily, in particular by journalists or the layman.

The editors recognize the variable quality and readability of the essays, and agree that a more uniform style is preferred. Achieving this is an ongoing process, and we will continue to work with the authors to prepare concise, well-written and well-illustrated essays suitable for a broad audience in future editions of the Arctic Report Card.

2. Many of the figures need editing to give the entire documents a common style.

The editors recognize that the quality of the figures, like the essays, is of variable quality. We agree that a more uniform style is preferred and will continue to work with the authors to achieve this in future editions of the Arctic Report Card.

3. Most of the highlights (I liked them) in front of each chapter are fine. They document that the past year was exceptional, with a range of changes exceeding anything in the past.

The editors appreciate the comment about the use of highlights at the beginning of each essay.

4. The (mostly) international teams of authors are fine; I do know many of them as excellent scientists. So, if NOAA spends the time and care to get this report into a proper shape, it will make an impact.

The editors appreciate the comment about the international teams of authors. The editors also recognize that there remain essays without sufficient breadth of international authorship, and they will continue to encourage the addition of authors from other countries.

5. The documentation provided for the statements of the individual chapters is very uneven.

The reviewer’s meaning is not clear to the editors.

6. Many figures need better labeling.

The editors agree that the quality of the figures is somewhat variable. See response to item #2 above.

7. Response to the notes for reviewers:

pt. 1 is OK.

pt. 2: Too much technical language and acconyms.

The editors will continue to encourage the authors to use less technical language, where appropriate, and minimize the use of acronyms in future editions of the Arctic Report Card.

pt. 3 is OK

pt. 4 is OK

pt. 5 is not yet OK: clear partly yes; reliable yes; concise mostly.

The editors will continue to work to achieve a clear, reliable and concise description of the current state of the Arctic.

INDIVIDUAL COMMENTS CARBON DIOXIDE (CO2) AND METHANE (CH4) Report is not written in a very clear way, no causal relations are described. No input from the seafloor considered. Here are some new data which need consideration, in particular when relating CO2 to "climate driving" (first paragraph of the report):

It is not the primary purpose of the Arctic Report Card to describe causal relationships. The primary purpose is to present observations, and explain them if the explanation is widely accepted and published in the peer-reviewed literature. The editors note that the paper by Humlum et al. (2012) is still *in press* today (3 November 2012) and thus not available to the authors of the greenhouse gas essay. The editors agree that the essay does not explicitly refer to input from the seafloor, but note that the essay does say that there is no direct evidence that either Arctic emissions of $CH_4$ or the net balance of C from $CO_2$ are changing. Emissions from the seafloor are implicit in the latter statement.

Figuren viser konsentrasjonen av CO2 i atmosfæren siden 1980 (grønt), jevnt stigende opp mot 390 ppm i dag. Blå kurve viser hvordan overflatetemperaturen i havene har endret seg, mens rød kurve viser endringer i den globale lufttemperaturen. Legg merke til hvordan CO2-

kurven undulerer i takt med årstidene, forårsaket av endringer i havtemperatur og fotosyntesen i den terrestriske biosfæren. Illustrasjon: Humlum et al., 2012

[Legend translation by JRL: "The figure shows the concentration of CO2 in the atmosphere since 1980 (green), steadily increasing up to 390 ppm today. The blue curve shows how the surface temperature in the oceans has changed, while the red curve shows changes in the global air temperature. Note how the CO2-curve oscillates seasonally, caused by changes in the ocean temperature and the photosynthesis in the terrestrial biosphere. Illustration: Humlum et al., 2012"]

Figuren viser globale endringer av CO2 i atmosfæren siden 1980 (grønt), global overflatetemperatur i havene (blå) og global lufttemperatur (rød). Legg merke til at grønn kurve ligger etter både blå og rød kurve. Illustrasjon: Humlum et al., 2012

[Legend translation by JRL: "The figure shows the global changes in CO2 in the atmosphere since 1980 (green), the global surface temperature in the oceans (blue)  and the global air temperature (red). Note that the green curve is behind the blue as well as the red curve. Illustration: Humlum et al., 2012"]

## Referanse:

Ole Humlum, Kjell Stordahl og Jan-Erik Solheim: The phase relation between atmospheric carbon dioxide and global temperature; Global and Planetary Change, 2012.

Table 1A: Is there not a station in Tiksi? Should Cdioxide and Methane not be related to ice?

The editors note that there is a station at Tiksi, but the authors point out that the record is too short to be included in the data analysed for this essay.

Regarding the second question, is the reviewer speculating that carbon dioxide and methane (concentrations?) are related to ice (sea ice?)? Arctic Report Card authors are discouraged from speculating. If the reviewer knows of studies published in the peer-reviewed that demonstrate a relationship between sea ice and these gases, it would have been useful if this information had been provided.

Section 1: ATMOSPHERE 1.1 AIR TEMPARATURE, ATMOSPHERIC CIRCULATION AND CLOUDS-Very good section.--Fig. 1.2 Why no marine observations?
The figure is for land stations only because insufficient offshore data are available.

1.2 OZONE AND UV RADIATION General: highly technical language, too many accronyms (some of them not explained at all), several phases unclear or unprecise. This section needs more work.

The editors agree that this is a technical presentation (and we continue to encourage the first author to remember that he is writing for a broad audience), but also think that the essay is well written. All the acronyms are now expanded in full. It would be helpful to know which phrases are unclear or imprecise. If the reviewer does not document those for us, we can not make improvements.

260 Ozone levels..."larger"..? Rather than “larger”, ozone levels are now “higher”.
334/335 Sentence is not clear. The sentence has been modified to make the meaning clearer.
395-400 many small localities - geography known to everybody? The editors agree that in this and other essays there are many place and feature names that some readers might not be familiar with. Consequently, we are considering adding maps to future editions of the Arctic Report Card.

Section 2: SEA ICE AND OCEAN
2. 1 SEA ICE Very important highlights, demonstrating that this year is truely exceptional. Decrease of old ice should get its own "highlight".
The continued decrease of multiyear ice now has its own highlight.

-616/618 ?trends. Should be rephrased to be more precise.
The text now states simply and clearly that sea ice extent is decreasing in all months and virtually all regions.

2.2 OCEAN Broad, but irregular international participation. Where are Schlosser, Dmitrenko, Timokhov? Otherwise fine text with good figures. Section

The editors will pass these names to the lead author who will be encouraged to consider them as possible future co-authors of the essay if they have material to contribute.

3: MARINE ECOSYSTEM
3.1 ARCTIC OCEAN PRIMARY PRODUCTIVITY-Excellent highlights
The reviewer’s comment is much appreciated.

-Fig. 3.3 Labelling too small. Are these annual means? What is (c) mean stratification?

The figure labels have been enlarged and the caption has been improved to explain what the mean values mean.

3.2 CETACEANS AND PINNIPEDS

2253 What are Arcric "core"....? The editors believe that the meaning of “core” is clear. No change has been made.

1302 Acoustic Ecology - Excellent chapter! The reviewer’s comment is much appreciated.

3.3 ARCTIC BENTHOS-Excellent and well written chapter.

The reviewer’s comment is much appreciated.

1616 HAUSGARTEN needs some explananation and reference.

Further information about the purpose of HAUSGARTEN, including a reference, have been added.

3.4 SEABIRDS

1778 ff: There must be other contaminants in addition to mercury.

The paragraph has been modified and it is now clear that there are other contaminants and that mercury is used here as an example.

3.5 PROJECTED IMPACTS...

1911 ???FMP Section

FMP is a fisheries management plan, which was added during a minor rewrite of this paragraph while the essay was being reviewed.

ECOSYSTEM OBSERVATIONS IN BARROW CANYON-Ok, but a very special case.

The editors agree that this essay is very specialized in terms of geography. For the moment, we have no objection to this, as the Distributed Biological Observatory is a new long-term observing activity that will benefit from the exposure in the Arctic Report Card. However, we will review this situation in future and assess whether the focus should remain on the DBO or be expanded to be more pan-Arctic in scope.

4: TERRESTRIAL ECOSYSTEM

4.1 VEGETATION-Very good and important highlights.

The reviewer’s comment is much appreciated.

2143ff. Any relationship to permafrost?

The penultimate sentence of this paragraph notes that deeper snow and resultant winter soil warming led to increases in shrub growth. This is sufficient allusion to permafrost changes.

2196 ..west central Greenland- this must be the coast? Central Greenland is under the ice sheet. The geography has been clarified to make it clear that this sentence refers to ice-free areas of central west Greenland.

2215 ITEX network?
ITEX is defined in full earlier in the essay.

4.2 LEMMINGS-Very good chapter
The reviewer's comment is much appreciated.

4.3 ARCTIC FOX-Very good, clear and concise
The reviewer's comment is much appreciated.

4.4 CARIBOU AND REONDEER-Fine chapter
The reviewer's comment is much appreciated.

3085 ....yet to be...analyzed Section
"yet to been analyzed" has been corrected to "yet to be analyzed'.

TRENDS IN ARCTIC WADERS-Chapter looks a bit immature

The editors acknowledge the reviewer's comment. However, since this is the first time that Waders have been included in the Arctic Report card, the editors believe that the apparent immaturity is not a significant issue. The essay will mature as more data become available in the future and the essay is updated. In any event, the authors did make some significant improvements in the interest of making the essay more comprehensive and thus a little more mature.

Table 1: Incomplete explanations/labeling: Known population trends? -
This question no longer applies, as the authors deleted the table.

Table 3: Units of trends?
This question no longer applies, as the authors deleted the table.

-EAAF??
This meaning of EAAF was added while the essay was out for review.

5: TERRESTRAIL CRYOSPHERE
5.1.SNOW-Very good and clear chapter.

The reviewer’s comment is much appreciated.

- Figs. need larger labeling

The size of the labels in the figures has been increased.

5.2 MOUNTAIN GLACIERS...-Very good chapter

The reviewer’s comment is much appreciated.

5.3 GREENLAND ICE SHEET-Excellent chapter, important highlights

The reviewer’s comment is much appreciated.

Fig. 5.11 ff: Figures suddenly change style

The editors recognize that there is some variability in the style of figures throughout the Arctic Report Card. The authors are provided with style guidelines, but unfortunately they don’t always follow them. We will continue to encourage authors to provide figures that follow the style guidelines.

Fig. 5.17: Explanation is not clear - entire ice sheet?

The figure caption has been amended to make it clear that the reconstruction is for the entire ice sheet.

5.4 PERMAFROST-Very good chapter, excellent highlights

The reviewer’s comment is much appreciated.

Reviewer 5

Comments on final draft Arctic Report Card 2012

| Section | Comment |
| --- | --- |
| 1 Atmosphere | General comment that use of subjective language such as deadly cold / record storms / super storm / quite average etc. is unique to this section of the report card (other sections use a much more technical language style), and may detract from the objective reporting style of the report card which makes it useful as a factual resource for many users.<br>Subjective/emotional language has been removed. |
| 1 Atmosphere<br>Lines 75 - 90 | The use of many different time periods for the relative statements is confusing (2003-2010, 1981-2010, 1971-2000, 2001-2011) and makes it difficult for the reader to understand clearly the characteristics of 2011/12. For example, para 75 refers to 2003-201 but Figure 1 identifies anomalies relative to 1981-2010. And figures 1.1, 1.2, 1.3 and 1.4 all use different reference periods.<br>The editors acknowledge and agree with the reviewer's statement. We continue to work with all Report Card essays to achieve greater uniformity and consistency for reference periods. |
| 1 Atmosphere<br>Lines 145 - 150 | Unit inconsistency: mph and m/s. The other sections of the report card consistently use SI units.<br>English/Imperial units have been converted to SI units. The editors thank the reviewer for pointing out this mixing of units. |
| 1 Atmosphere<br>Line 180 | The linkage drawn between cloud cover and sea is helpful. Would it be possible to reference a specific figure in section 2 here, to point the reader to the information on negative sea ice anomalies (Figure 2.2)?<br>A reference/link has been added to the Sea Ice essay. |
| 1 Atmosphere / 2 Sea Ice | The August 2012 storm is referenced in section 1 and section 2. The authors might consider the addition of a "side box" to describe the nature / interesting aspects of this storm in more detail if it is truly a unique feature of the 2011/12 period.<br>This is a good suggestion, which we propose to do in the Arctic chapter of the BAMS State of the Climate 2012 report to be published in ~mid-2013. |
| 2 Sea Ice | A good overview<br>The reviewer's comment is much appreciated. |
| 5 Terrestrial Cryosphere | The absence of the lake ice section is noticeable and it is unfortunate to not have that complete picture of the cryosphere conditions this year. Overall though, a good summary<br>The editor's agree with the reviewer. A lake ice essay was invited in June 2012, but unfortunately the lead author was not able to prepare one in time for Report Card 2012. We anticipate that there will be one in the BAMs State of the Climate 2012 report to be published in ~mid-2013. |
| X Greenhouse Gases<br>CO2 and CH4 | *$CH_4$ is a potent greenhouse gas; it causes about 25 times more warming over 100 years than emission of an equal mass of $CO_2$.* Include reference (Forester |

| | |
|---|---|
| 1st para | et al., 2007)<br><br>The reference has been added to the text. |
| X Greenhouse Gases CO2 and CH4<br>2nd para | *If Arctic soils remain water-saturated, a larger fraction of carbon will be emitted as $CH_4$ as a result of anaerobic microbial activity. On the other hand, if Arctic soils drain as permafrost thaws, a larger proportion of carbon will be emitted as $CO_2$.* Suggested clarification by addition of underlined text.<br><br>"of carbon" has been added as suggested.<br><br>Schaefer et al., 2011 citation appears to be missing in "References" section.<br><br>The reference has been added to the reference list. |
| X Greenhouse Gases CO2 and CH4<br>4th para | *The recent upward trend in $CH_4$ is thought to be related mainly to a rebound of natural emissions in the tropics after a prolonged period of lower-than-average precipitation.* It would be helpful / more robust to explicitly have this statement referenced to one or more citations.<br><br>Two references have been added: Bousquet et al. (2011) and Dlugokencky et al. (2009) |
| X Greenhouse Gases CO2 and CH4<br>5th para | The IPD is a very useful concept for understanding relative influence of source regions on Arctic atmospheric concentrations, however there is no citation related to mid-latitude emission trends, nor information presented on mid-lat emission trends over the past decade. Consequently, the inference that IPD ***mainly*** reflects Artic emission changes without more precise definition of this source region (e.g.: north of 60N, north of 40N?) would benefit from reference to published works, or greater specificity in this report. Similarly, while the statement "*As yet, there is no direct atmospheric evidence that either Arctic emissions of $CH_4$, or the net balance of C from $CO_2$, are changing.*" may well be correct it would be stronger and more insightful with clarification of exactly what region is considered "Arctic" in context of emission sources and reference to more recent published analysis. Given current country attention to development of CH4 mitigation plans this concept of IPD and interpretation of trends over the past ~15 years warrants a more robust presentation here.<br><br>The IPD paragraph has been modified in response to this request, including the addition of a reference to the original IPD paper by Dlugokencky et al. (2003). The Arctic region that is considered here was, and still is, defined at the beginning of the paragraph as 53° to 90°N. The editors consider the presentation to be sufficiently robust for the Arctic Report Card. |
| General comment | C stores are referenced in sections 3.1, 4.1 and in section GHGs. Line 1185, 2095. Even a simple cross reference between sections would be helpful to orient the reader to finding C related information in the different sections.<br><br>Further connections have been added among essays per this request. |

| | |
|---|---|
| | Also see final comment below. |
| General comment | Sections 3 and 4 make reference to growing season temperature patterns. In this regard it might be of interest to see in section 1 an indication of changing seasonal or monthly temperatures (max, min, etc) as context for subsequent sections (for example 2155, 2165, 2205).<br><br>The editors agree that this is a good suggestion. We continue to strive to have the *Air Temperature, Atmospheric Circulation and Clouds* essay ‘serve’ the other essays, but it is not always possible to cover all needs and eventualities. We will continue to address this issue in future Arctic Report Cards. |
| General comment | The Arctic Report Card in this draft continues the presentation of helpful and insightful synthesis of current conditions in historical context. I recognize that the Report Card is not intended to provide an integrated assessment across disciplines, but a few small additions to connect the phenomenon across sections would simply make a good report, even more interesting.<br><br>The editors accept this comment and note that every effort has been made to connect the essays. The version of the report sent for review contained a number of connections, and more connections were added while the Report Card was out for review. The editors feel that a comprehensive set of connections has been made. |

**Reviewer 6**

**Terrestrial ecosystems**

Well written chapter with interesting updates and case studies. Easy to read.

No response required, except thank you.

P. 69 Highlights

The time spans over which the changes have taken place need to be stated (l. 2062; l. 2065)

The periods of record have been added.

Chapter 4.3 Arctic Fox

P 89, line 2856: a reference needs to be given for “international studies”

The text has been modified and two references have been added.

P. 90. There is a repetition regarding the competition between Arctic fox and red fox (lines 2860-2865 versus 2885-2890).

The material about the Red fox has been reorganized and consolidated in one place between lines 2775 and 2784.

Page 92. Fig. 4.7, legend. There needs to be inserted a reference giving the source of the data.

A reference to the data source has been added to the caption and the reference list.

Page 92, References. The reference to ABA 2012 is not valid. The Arctic Biodiversity Assessment by CAFF is not due before 2013.

The reference has been modified to make it clear that it is unpublished, but scheduled for publication in 2013.

Chapter 4.4 Caribou / Reindeer

Page 96, Fig. 4.9. There needs to be an X and Y axis label to make the figure understandable. And it is not clear what the different colors represent and why they vary in thickness.

The figure and caption have been improved to make it easier to understand the information presented. Instead of axis labels, the axes are explained in the caption.

Page 98: No reason to mention that 2012 data still have to be analysed (delete): lines 3085 and 3088.

The information has been deleted.

Page 99, line 3131: "The domestic reindeer industry" is a bit of an awkward expression. Can "industy" be replaced by "stocks"?

The editors are comfortable with "domestic reindeer industry".

Line 3132: for a non-expert, it is difficult to understand why the collapse in domestic reindeer caused an increase in the wild population. A sentence to explain why would be useful.

The increase in the wild herd size is now explained.

**Trends in Arctic Waders (Shorebirds)**

Interesting chapter highlighting one of the major Arctic biodiversity conservation concerns and the need for international solutions; however, too long for the Arctic Report Card format.

The editors are comfortable with the length of the essay, as this is the first time the topic has appeared in the Arctic Report Card. We will pay attention to the length in future essays and updates.

Table 2 can be left out; the information is summarized in Fig. 1. Likewise, Table 2 is not really suited for a summary paper.

Table 2 mentioned in the first sentence above has been deleted after the editor confirmed that it duplicated information in Figure 1. Table 2 mentioned in the second sentence is not the same as that in the first sentence; it is Table 3 and was deleted by the authors in their response to the review.

Highlight, first bullit: "come from" should be replaced by "link" as originally written; fourth bullit: replace "are" with "is" after African-Eurasian Flyway.

These changes have been made.

First page, last line: delete "also known as shorebirds"

The editors disagree. Not all readers will know that waders are also shorebirds. Consequently, the editors prefer that the phrase "also known as shorebirds" remains.

Page 8: "Central Asian" (in bold) should be "Central Asia"

This change has been made.

Page 10 Threats: the track changes made are incorrect and make no sense. The message is that the trends are difficult to interpret because it is unknown during which part of the annual cycle (which is separated in time, space and anthropogenic pressure) populations are limited.

The editors note that changes made before the essay was sent for review did not alter the substance of the original essay. The changes were stylistic not technical. Hence, the reviewer's comment is directed at the authors. The reviewer is saying the same thing as the authors in a more concise fashion.

Page 10, Case study Spoon-billed Sandpiper: the authors should avoid using terms like “charismatic”, “flagship species”; keep the text to the factual status.

Subjective/emotional terms have been deleted.

Page 11, line 5: “shown by modeling” should be replaced by “predicted by modeling” .

This change has been made.

**Ecosystem Observations in Barrow Canyon: A Foci for the International Distributed Biological Observatory**

Neat case study of a new joint international interdisciplinary research and monitoring effort.

No response required, except thank you.

Highlights: First bullit: spell out what DBO stands for.

This has been done.

**Marine Ecosystems**

Arctic Ocean primary productivity

Well written and interesting overview.

No response required, except thank you.

Cetaceans and Pinnepeds

The first chapter refers to the ABA by CAFF; however, the chapter just makes a listing of the pan-Arctic distribution of the species; I lack a story and conclusions.

The editors do not share the reviewer’s concern. This section gives a brief, adequate and up-to-date summary of the current status of marine Arctic mammal biodiversity. No “story and conclusions” are necessary.

Page 49, line 1313: why is it surprising that sub-Arctic whales were recorded? It is known that they occur in the Fram Strait during summer.

It is now noted that Spitzbergen bowhead whales are critically endangered; hence the importance of their winter singing.

Line 1314: “,respectively” should be inserted after “March”.

This addition has been made.

Line 1319: “Acoustic habitat” is an expression which needs to be explained to a non-expert reader.

‘Acoustic habitat’ is now explained as ‘the sounds underwater to which animals are exposed’.

Line 1333: the expression “ecological niche factor analysis” is a technical term which could easily be replaced by a more non-technical expression.

The term has been removed to avoid confusion.

Arctic benthos

Interesting pan-Arctic overview.

Page 52, Fig. 3.5: what shows the punctuated line in the diagram? If it is not relevant to the story, it should be removed.

The editors asked the author to explain this while the essay was out for review. The explanation is now in the figure caption.

Page 54, line 1543: there needs to be a reference to the study in Greenland.

References (Krause-Jensen et al. 2012; Blicher et al. 2010) are already provided earlier in the paragraph.

Page 55, line 1570: there needs to be a reference inserted

Line 1570 is on page 56 and it is a blank line between a title and a paragraph. The editors are uncertain as to what the reviewer is requesting.

Seabirds

Highlights, second bullit: spell out SST

This has already been done at the request of another reviewer.

The authors might like to mention the recent large-scale analysis of Atlantic Kittiwake overwintering areas detected by geolocators (see M. Frederiksen et al in Diversity and Distribution 2012). First of its kind and providing new insight into overwinter strategies of Arctic seabirds.

Reference is now made to Frederiksen et al. (2012) in the text and the reference has been added to the reference list.

Projected impacts of climate change…

Interesting chapter on a new concerted initiative.

No response required, except thank you.