STATE OF THE CLIMATE IN 2003

D. H. Levinson[14] and A. M. Waple,[14] Eds.

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ABSTRACT—D. H. Levinson[14] and A.M. Waple[14] (Eds).

The earth's climate was influenced by a moderate El Niño in the tropical Pacific Ocean at the beginning of 2003. This ENSO warm event developed during October–November of 2002, and eventually dissipated during March–April 2003, giving way to near-neutral ENSO conditions for the remainder of the year. Despite the cessation of El Niño during the boreal spring, the ENSO warm event affected regional precipitation anomalies over a broad area of the Pacific basin, including wet anomalies along the west coast of South America, and dry anomalies in eastern Australia, the southwest Pacific, and Hawaii.

The global mean surface temperature in 2003 was within the highest three annual values observed during the period of regular instrumental records (beginning in approximately 1880), but below the 1998 record-high value. Global surface temperatures in 2003 were 0.46°C (0.83°F) above the 1961–90 mean, according to one U.K. record, which ranked as third highest in this archive. In the U.S. temperature archive, the 2003 anomaly was also 0.46°C (0.83°F), equivalent to the 2002 value, which ranked second over the period of record. Similar to the surface temperature anomalies, satellite retrievals of global midtropospheric temperatures ranked 2003 as third warmest relative to the 1979–98 mean value.

The hurricane season was extremely active in the Atlantic basin, with a total of 16 tropical storms, seven hurricanes, and three major hurricanes in 2003. Five of these tropical cyclones made landfall in the United States, three made landfall in northeastern Mexico, and a tropical storm affected Hispañola. In addition, Nova Scotia and Bermuda experienced devastating impacts from hurricanes in 2003. Another notable aspect of the season in the Atlantic was the formation of five tropical storms over the Gulf of Mexico, which tied the season high observed in 1957. In addition, three tropical storms formed outside of the normal (June–November) hurricane season in 2003—one in April and two in December—which made this the first season since 1887 that two tropical storms have formed during December in the Atlantic basin. Also of note was the below-normal activity in the eastern North Pacific basin. There were no major hurricanes in this basin during the 2003 season, which made this the first year since 1977 with no category 3–5 storms. Despite the below-normal activity, four tropical cyclones made landfall on the Pacific coast of Mexico, two as hurricanes and two as tropical storms, which was twice the long-term mean.

The summer of 2003 was one of the warmest on record across parts of Europe, where a heat wave affected most of Central and Western Europe. Two distinct periods of exceptional heat occurred during the season—the first in June and the second during the latter half of July and the first half of August. The July–August heat wave was the more serious of the two, since it coincided with the normal peak in summer temperatures and was accompanied by an almost complete absence of rainfall. The high temperatures and dry conditions exacerbated forest fires that burned across southern France and Portugal in July and August. The record heat wave spread across most of Western Europe in August, and it was likely the warmest summer since 1540 in parts of Central Europe. In France, 11,000 heat-related deaths were reported between late July and mid-August. In Germany, both June and August were the warmest such months since at least the beginning of the twentieth century. The summer was also the hottest in Germany since 1901, and, with the exception of some stations in northern and northwestern Germany, it was the hottest summer since the beginning of recorded measurements.

Other climatic events of note during 2003 included 1) record wet conditions across parts of the southeast, mid-Atlantic, and eastern coast of the United States; 2) record cold temperatures and anomalous June snowfalls in European Russia; 3) 546 tornadoes during May 2003 in the United States, which was an all-time record of reported tornadoes for any month; 4) continuing drought conditions across the western United States, with some areas experiencing their fourth and fifth years of significant precipitation deficits; 5) severe bushfires in eastern Australia in January, the worst wildfire season on record in British Columbia during August, as well as severe wildfires across southern California in October; 6) above-average rainfall across West Africa and the Sahel, which had its second wettest rainy season since 1990; 7) a return to normal rainfall across the Indian subcontinent during the summer monsoon; and 8) a near-record extent of the Antarctic ozone hole, which was 28.2 million km^2 at its maximum in September 2003.

The lack of any major hurricanes, the development of only one category 2 hurricane, as well as the record late formation of the first hurricane of the season made 2003 a below-normal year in the ENP basin. This was strongly reflected in the ACE index (Bell et al. 2000) for the 2003 ENP hurricane season. The ACE index for the 2003 season was 48.67×10^4 Kt^2 (G.D. Bell 2004, personal communication), which was approximately 37.5% of the mean value of 129.7×10^4 Kt^2 and approximately 43% of the median value of 113×10^4 Kt^2 determined from the 1971–2000 base period climatology. Several environmental factors influenced the observed anomalous conditions, and these included: ENP basin SSTs, higher total vertical wind shear over the ENP (see Figs. 4.11a–b and discussion in section 4bi), the phase of ENSO, and the phase of the QBO in the tropical lower stratosphere.

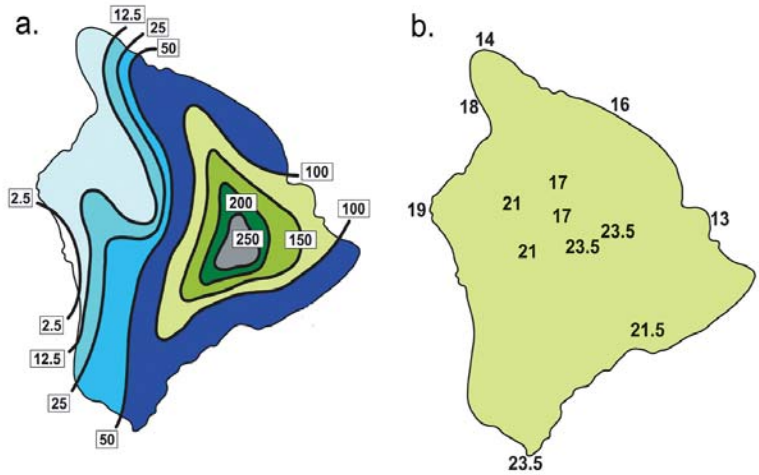

Fig. 4.19. Rainfall totals (mm; panel a) and peak wind gusts (m s^{-1}; panel b) observed on the Big Island of Hawaii during the passage of H Jimena on 31 Aug and 1 Sep. (Courtesy of A. Nash, NOAA/CPHC.)

Whitney and Hobgood (1997) developed an empirical relationship between SSTs and the maximum intensities of tropical cyclones in the ENP basin. They found that only 11% of ENP storms reach 80% of the maximum potential intensity (MPI) in the ENP, while tropical cyclones that formed west of 110°W tended to reach a higher percentage of their MPI than storms that developed farther east. In 2003, a majority of the named storms and hurricanes formed east of 110°W, which would inhibit their ability to intensify to their MPI. This was likely influenced by the presence of enhanced vertical wind shear in the ENP basin during the 2003 season (see section 4bi, Fig. 4.11).

SSTs in the ENP are influenced by the phase of ENSO, which was neutral during the summer and fall of 2003. An equatorial Pacific warm event (i.e., El Niño) typically increases SSTs in the ENP, thereby enhancing the observed intensity of tropical cyclones in the basin. However, the climatological frequency of tropical cyclones in the ENP basin does not necessarily support this physical link. Using tropical cyclone data from 1963 to 1993, Whitney and Hobgood (1997) found that there was very little difference in the frequency of tropical cyclones over the ENP basin between El Niño and non–El Niño years. However, this result may be due to the timing difference between the peak of the ENP hurricane season in September each year and the peak in the warmer-than-normal SST anomalies associated with El Niño events during the Northern Hemisphere winter. In fact, they found that the phase of the QBO was a more important factor than ENSO in influencing the maximum intensity of tropical cyclones in the ENP, mainly by affecting the propagation speed and the outflow circulation from the upper levels of the tropical cyclone. Their 31-yr study of ENP storms showed that tropical cyclones tended to reach a higher percentage of their MPI, as well as a higher maximum intensity, when the QBO was in its westerly phase at 30 mb in the tropical stratosphere. The observed influence of the QBO on tropical cyclone intensities for the ENP basin found by Whitney and Hobgood (1997) was similar to that found in the Atlantic basin by Gray (1984) and Shapiro (1989), among others.

During late 2002, the QBO switched from the westerly to the easterly phase, and the phase remained easterly through the 2003 hurricane season in the ENP. Therefore, a combination of environmental factors inhibited the development and intensification of the tropical storms and hurricanes to reach higher intensities in the ENP, with the presence of the easterly phase of the QBO in the tropical lower stratosphere, as well as the enhanced vertical wind shear in the basin, likely influencing the observed magnitude and frequency of tropical storms and hurricanes during the 2003 season.

5. POLAR CLIMATE—A. M. Waple,[14] R. C., Schnell,[23] and R. S. Stone[23]

a. *Antarctic*

i) Surface climate

Annual temperature trends over the last 53 yr across the southern high latitudes are shown in Fig. 5.1. Marked seasonal and spatial differences are evident from the stations shown, with eastern Antarctica

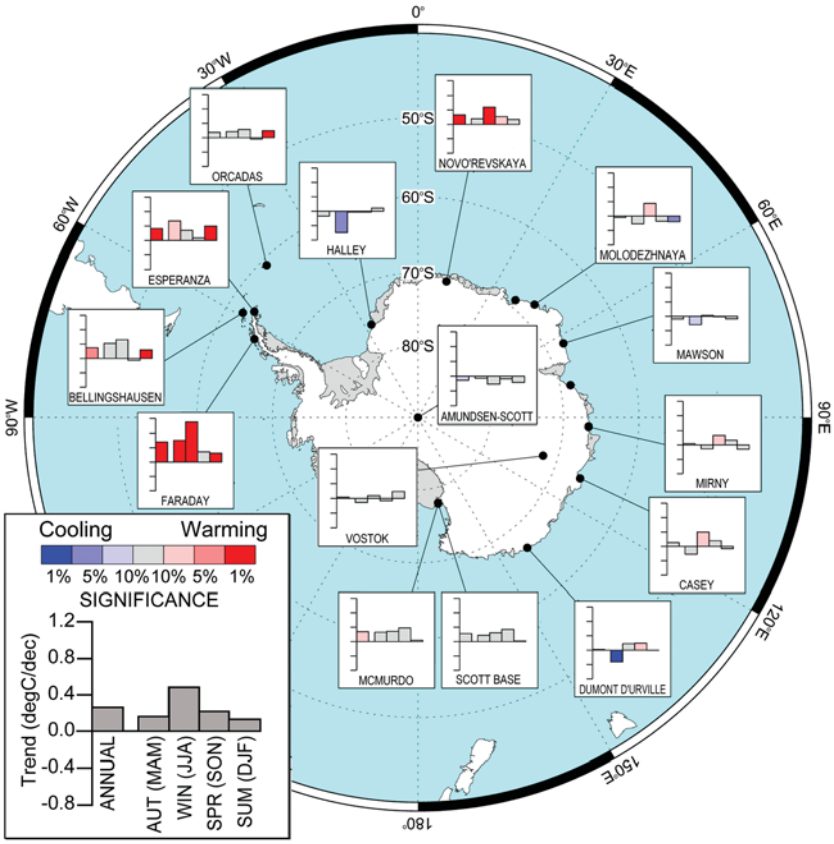

Fig. 5.1. Decadal temperature trends (in °C) for selected Antarctic stations. (Courtesy of G. Marshall, British Antarctic Survey.)

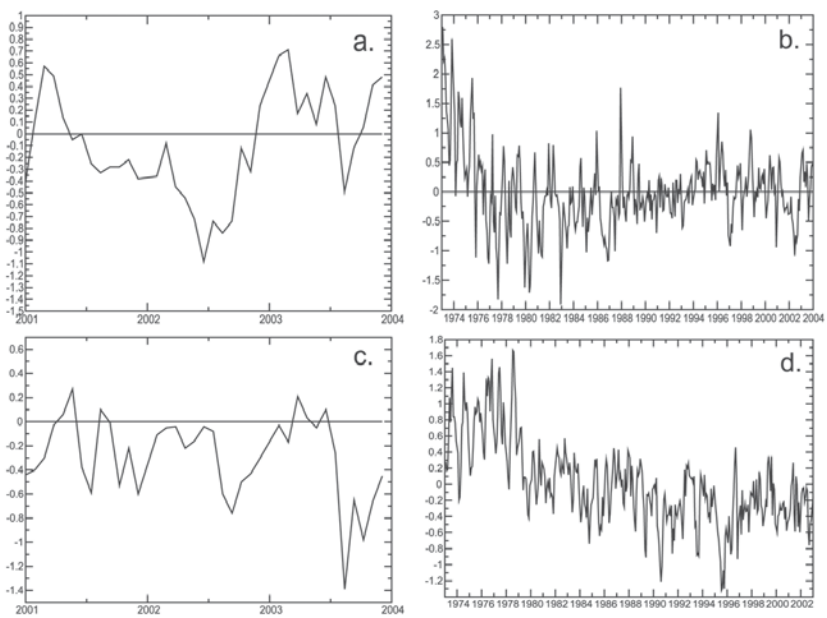

Fig. 5.2 . Monthly sea ice extent anomalies for (a) the NH for 2001–03, (b) the Northern Hemisphere from 1973 to 2003, (c) the SH for 2001–03, and (d) the SH from 1973 to 2003. Anomalies are departures from the 1973–96 base period.

having little or no significant annual temperature trend, while the Antarctic Peninsula has generally warmed over the last 50 yr. Coincident with this warming trend, ice shelves have retreated on the Antarctic Peninsula along with decreases in sea ice extent in the Bellingshausen Sea (e.g., Vaughan and Doake 1996), while sea ice concentration and length of season have increased in the Ross Sea, as well as over much of eastern Antarctica, (e.g., Stammerjohn and Smith 1997). Reliable measurements are difficult to obtain for Antarctica given the harsh conditions and transience of scientific personnel; however, from the limited data available, the last decade has been colder than average in contrast to the general increasing temperature trend from the late 1950s to the early 1990s, averaged across the continent. The June 1991 eruption of Mt. Pinatubo may have had a marked influence on Antarctic temperatures for several subsequent years (Jacka and Budd 1998), likely accounting for some of the decadal cooling. Overall, 2003 was cooler than 2002, but close to the 10-yr mean.

Decreases in sea ice, in response to warmer ocean and surface air temperatures, amplify polar climate change through ice albedo feedback effects. Sea ice extent surrounding Antarctica also regulates the production of Antarctic bottom water formation, which helps to drive global ocean circulation. According to the U.S. National Snow and Ice Data Center (NSIDC), sea ice covers approximately 17–20 million km^2 of the Southern Ocean at its maximum in late winter. The seasonal decrease is larger in the Antarctic, with only about 3–4 million km^2 remaining at

summer's end, compared with approximately 7–9 million km^2 in the Arctic. As shown in Fig. 5.2a, in 2002, sea ice extent in the Antarctic was below average for much of the year. By year's end, sea ice extent had begun to increase in comparison to the 30-yr average, and for the first 6 months of 2003, sea ice extent was above average. A brief decrease relative to the mean was observed in early to mid-winter, and then a recovery to above-average sea ice extent occurred during the remainder of 2003. Sea ice surrounding the Antarctic continent has been increasing from the late 1970s to the mid-1990s (Fig. 5.2b), but this time series belies considerable seasonal and spatial variability. The early part (1973–78) of this sea ice record is determined using different instruments and may reflect data calibration problems. For further discussion on this aspect of the record, see Folland et al. (2001a).

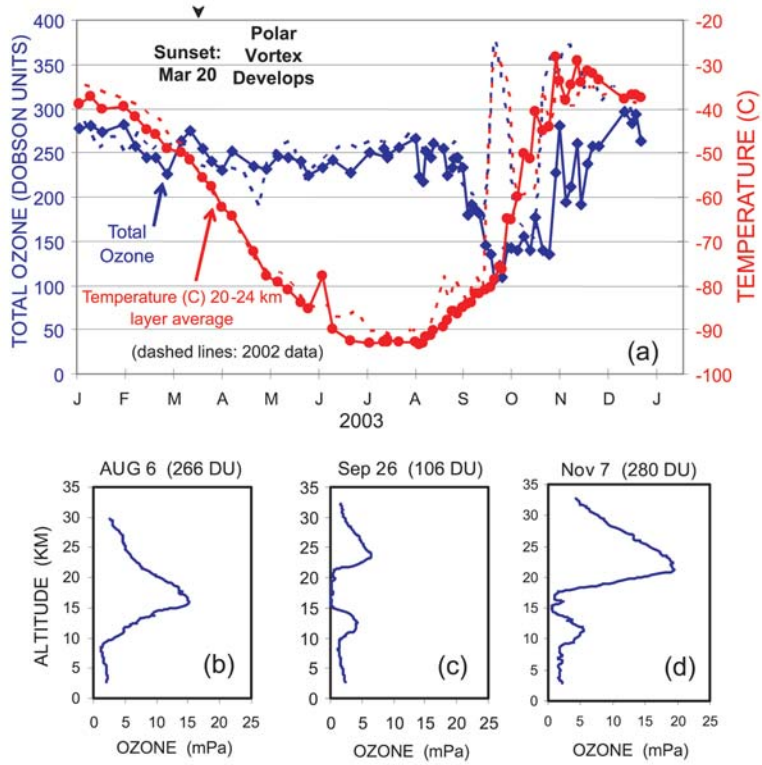

Fig. 5.3. (a) Summary of South Pole total ozone (in DU) and stratospheric temperatures (°C) measured by ozonesondes during 2003. Three selected profiles of altitude vs ozone partial pressure (mPa) are shown in the lower panels: (b) prior to the 2003 ozone hole, (c) the minimum total ozone, and (d) postozone hole. (Courtesy B. Johnson and S. Oltmans, NOAA/CMDL.)

ii) Antarctic stratospheric ozone

The NOAA/CMDL ozonesonde measurements at the South Pole for 2003 are shown in Fig. 5.3. The total column ozone (blue line) in Dobson units (DU) and temperature (red line) in the 20–24-km layer of the stratosphere illustrate the development of an average ozone hole over South Pole station. However, the extent of the ozone hole area (< 220 DU) measured

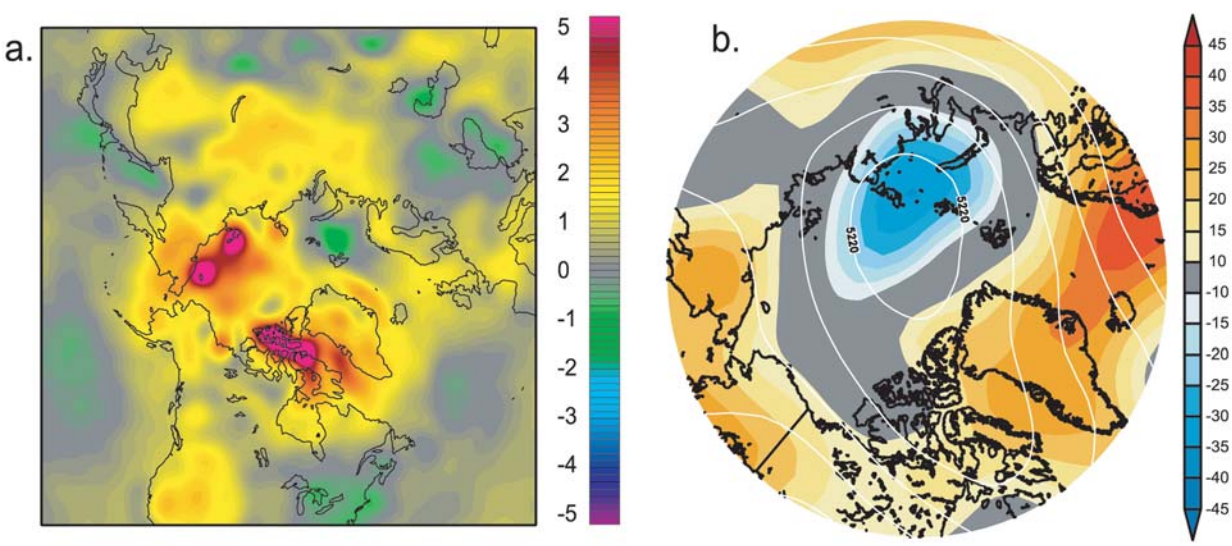

Fig. 5.4. (a) Mean annual surface air temperature anomalies (in °C) for 2003, with respect to the 1954–2003 mean (courtesy of B. Chapman); (b) mean annual 500-hPa height anomalies (m) for 2003, with respect to the 1968–96 mean.

by the National Aeronautics and Space Administration (NASA) Total Ozone Mapping Spectrometer (TOMS) instrument was near record levels at 28.2 million km^2. From June to early August, cold stratospheric temperatures and a stable winter/spring polar vortex provided favorable conditions for the formation of polar stratospheric clouds. These cloud surfaces enable the transformation of chlorine and bromine compounds into species that destroy ozone when sunlight returns to the Antarctic stratosphere.

The selected profiles from 6 August and 26 September show that ozone in the 14–21 km layer was nearly completely destroyed by the time the minimum total ozone column ozone of 106 DU was observed in mid-September. The 60% drop in total column ozone was equal to the 10-yr average loss of 60 ±6%. However, the record minimum total ozone remains at 89 DU measured at South Pole station on 6 October 1993. The ozonesonde measurements in 2002 (dashed lines in Fig. 5.3), show a large increase in stratospheric tempera-

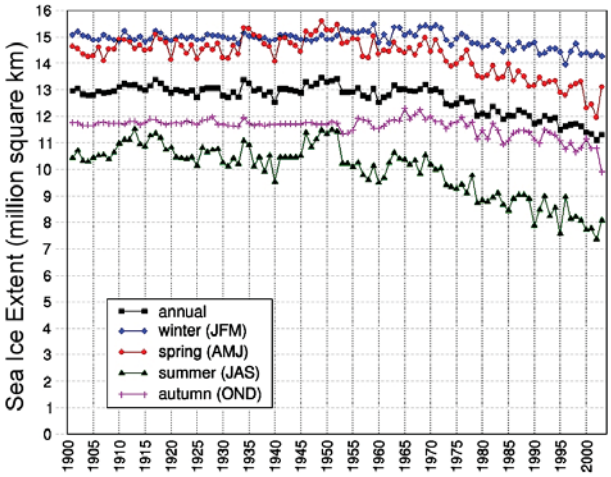

Fig. 5.5. Time series of annual and seasonal sea ice extent in the Northern Hemisphere, 1901–2003 (annual values from Vinnikov et al. 1999; seasonal values courtesy of B. Chapman, updated from Chapman and Walsh 1993).

DIMISHING SEA ICE IN THE WESTERN ARCTIC OCEAN—R. S. Stone,[23] G. Belchansky,[4] S. Drobot,[13] and D. C. Douglas[12]

Since the advent of satellite passive microwave radiometry (1978), variations in sea ice extent and concentration have been carefully monitored from space. An estimated 7.4% decrease in sea ice extent has occurred in the last 25 yr (Johannessen et al. 2004), with recent record minima (e.g., Maslanik et al. 1999; Serreze et al. 2003) accounting for much of the decline. Comparisons between the time series of Arctic sea ice melt dynamics and snowmelt dates at the NOAA–CMDL Barrow Observatory (BRW) reveal intriguing correlations.

Melt-onset dates over sea ice (Drobot and Anderson 2001) were cross correlated with the melt-date time series from BRW, and a prominent region of high correlation between snowmelt onset over sea ice and the BRW record of melt dates was approximately aligned with the climatological center of the Beaufort Sea Anticyclone (BSA). The BSA induces anticyclonic ice motion in the region, effectively forcing the Beaufort gyre. A weak gyre caused by a breakdown of the BSA diminishes transport of multiyear ice into this region (Drobot and Maslanik 2003). Similarly, the annual snow cycle at BRW varies with the position and intensity of the BSA (Stone et al. 2002, their Fig. 6). Thus, variations in the BSA appear to have far-reaching effects on the annual accumulation and subsequent melt of snow over a large region of the western Arctic.

A dramatic increase in melt season duration (Belchansky et al. 2004) was also observed within the same region of high correlation between onset of melt over the ice pack and snowmelt at BRW (Fig. 5.7). By inference, this suggests linkages between factors that modulate the annual cycle of snow on land and processes that influence melting of snow and ice in the western Arctic Ocean.

Causes of a Lengthening Sea Ice Melt Season

Belchansky et al. (2004) found that the duration of the sea ice melt season was correlated with the phase of the previous winter's Arctic Oscillation (AO) index (Thompson and Wallace 1998). Following positive AO index winters, melt onset has tended to be early, and the autumn freeze late, especially in the regional "hot spot" indicated in Fig. 5.7. Serreze et al. (2003) cautioned that while much evidence supports this view, there were notable exceptions. For example, the 2002 record minimum ice extent, which was dominated by a negative anomaly in the western Arctic, followed a winter of alternating AO indices. This anomaly was caused by abnormally warm atmospheric temperatures during spring, followed by a summer during which cyclonic surface winds exported sea ice from the region.

Spring appears to be a critical transition period in the annual cycles of snow and sea ice. A schematic of the synoptic pattern that persisted during March, April, and May of 1996, 1998, and 2002, years when melt onset was early, is shown in Fig. 5.7. During these

ture and ozone over the South Pole on 25 September, when a rare stratospheric warming event in the Southern Hemisphere forced an early breakup of the ozone hole. Therefore, with the return of near-average ozone hole conditions over the South Pole in 2003 there appears to be no immediate signs of long-term recovery, and 2002 remains an anomalous event.

b. The Arctic

1) Sea ice and temperature

Temperature over the Arctic basin for 2003 was warmer than average (Fig. 5.4a), with autumn and winter exhibiting the largest anomalies over the western half of the Arctic Ocean and moderate cool anomalies over the eastern part of the basin. This broadly coincided with the pattern of positive and negative height anomalies at the 500-hPa level in the region (Fig. 5.4b). Spring and summer were moderately warm over most of the basin. Temperature trends over the last 50 yr for the Arctic (not shown) illustrate significant warm-

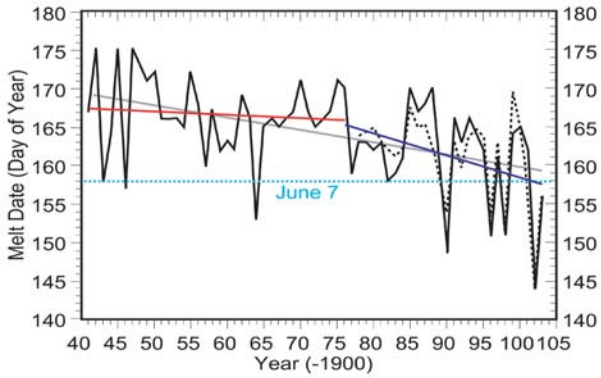

Fig. 5.6. Time series of snowmelt dates constructed for the NOAA/CMDL Barrow Observatory. Three linear regressions are plotted: an overall fit for 1941–2003 (thin black line), for all years prior to 1977 (red), and a third beginning in 1977 (blue). Results of an empirical model are also shown (dashed). The time series was compiled from direct snow depth observations, from proxy estimates using daily temperature records, and (beginning in 1986) on the basis of surface radiometric measurements (updated from Stone et al. 2002).

periods there was a complete breakdown of the BSA. The transport of warm, moist air into the Arctic was greatly enhanced by a persistent synoptic pattern that coupled a high pressure system centered over Alaska with a well-organized AL centered over the western Bering Sea. A mean back trajectory is shown in Fig. 5.7 relative to the region of long duration of sea ice melt.

Warm air advection associated with this synoptic pattern adds moisture to the Arctic atmosphere, increasing cloudiness. Prolonged effects of warm air advection (boundary layer turbulence), augmented by cloud radiative forcing can modify the microphysical structure of the overlying snow. This "ripening" may precondition the snowpack such that the melt is accelerated during May/June when solar insolation reaches its annual peak.

Significant ice melt also cannot occur until the insulating layer of snow atop the sea ice first melts. If snow accumulation on sea ice is low, and conditions favor an earlier ripening of the pack as described above, then the snow cover will melt more rapidly, advancing the onset of ice melt. Thus, reduced snowfall over the western Arctic Ocean in recent years may account, in part, for the decline in sea ice in that region.

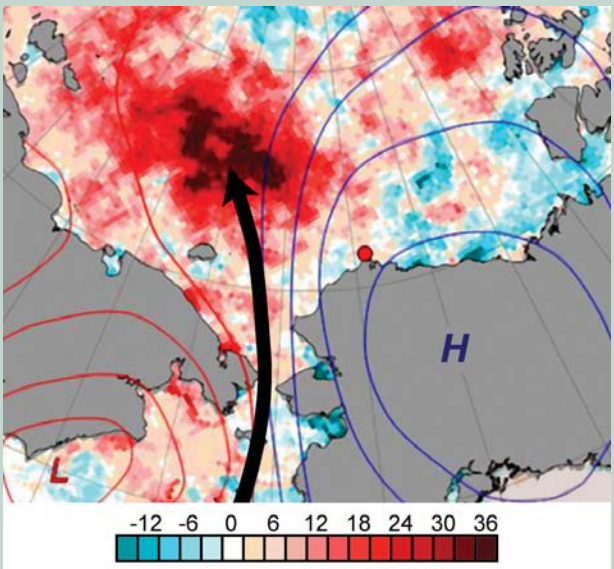

Fig. 5.7. Change in the melt season duration from 1979–88 to 1989–2001 determined from passive microwave-derived melt onset and freeze-onset dates (adapted from Belchansky et al. 2004; Fig. 6). The contours show, schematically, the composite synoptic pattern, and associated prevailing wind (arrow) at 850-hPa during March, April, and May, 1996, 1998, and 2002, preceding periods of extreme ice retreat in this region.

ing across the northern continents. However, it is unclear what trend has occurred across much of the central Arctic Ocean due to a lack of data. Much of the 50-yr trend in the land-based annual temperatures was derived from winter and spring anomalies, which, in the case of winter, exceeded 4°C in broad areas of North America and Russia.

Following the record low sea ice extent in 2002, there was modest recovery in 2003 to annual values similar to those in 2001 (Figs. 5.2b,c). Both spring and summer had large increases over 2002, but further sea ice extent decreases were evident in fall and winter, with fall having its lowest extent during the period of record (Fig. 5.5). Surface air temperature anomalies exceeded 4°C over the majority of the Arctic basin during October, and this aided in delaying freeze up across the sea surface, leading to a record-low sea ice extent for the month. The rate of refreezing remained low throughout November and December, which was reflected in the ice concentrations and extent. Sea ice extent anomalies for October also reached their lowest value for any month since the early 1970s (Fig. 5.2d). The low October sea ice was comparable only to 1995, when the large negative anomaly (over 1 million km^2) was sustained for several months, but did not quite reach the same value as for October 2003 (1.39 million km^2).

ii) Snowmelt

Snow cover for the Northern Hemisphere, including regions extending into the Arctic, is described in section 2d. However, presented here is snowmelt information for northern Alaska as well as an associated discussion of sea ice variability. Previous climate assessments (Lawrimore et al. 2001; Waple et al. 2002; Waple and Lawrimore 2003) documented an advance in the date of snow disappearance (melt date) in spring at the NOAA/CMDL Barrow Observatory (BRW). In this section, the time series of BRW melt date is updated, and the record is examined in the context of sea ice variations in the western Arctic Ocean, defined here as the region from the East Siberian Sea to the Beaufort Sea (see sidebar, p. 32).

Although 1999, 2000, and 2001 were years of moderately late snowmelt at BRW, 2002 was the earliest on record. In 2003, the melt date was again early (Fig. 5.6).

Since 1940, the spring melt at BRW has advanced by about 10 days (±4.8 days, 95% C.L.) and most of the advance has occurred since 1976. The break in the record coincided with shifts in other climatic as well as biological indicators of change (Hare and Mantua 2000). The observed variations in the annual snow cycle of northern Alaska are largely attributable to changes in atmospheric circulation related to intensification of the Aleutian low (AL), in conjunction with fluctuations of the Beaufort Sea anticyclone (BSA). On this basis, an empirical model was developed to predict melt dates at BRW (Fig. 5.6, dashed curve). About 80% of the variance in melt dates at BRW are explained by changes in snowfall during winter, and variations in spring temperatures and cloudiness (Stone et al. 2002).

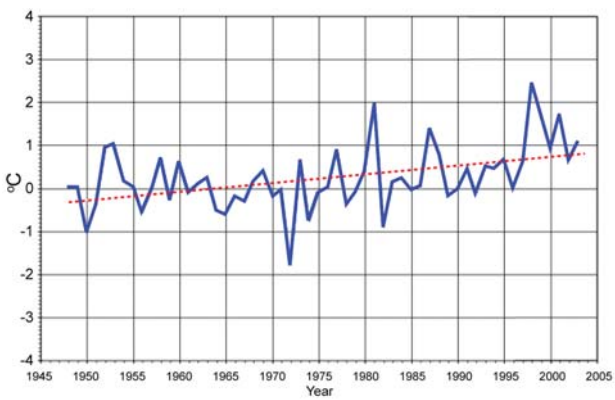

Fig. 6.1. Canadian nationwide annual temperature departures (blue line) and long-term trend (red line) for the period 1948–2003. Anomalies (in °C) were determined with respect to the 1951–80 base period. (Courtesy of the Meteorological Service of Canada, Environment Canada.)

6. REGIONAL CLIMATE

a. North America

i) Canada—D. H. Levinson[14] and D. Phillips[20]

(i) Temperature

The majority of Canadian provinces and territories experienced above-normal temperatures in 2003, and the country as a whole had an annual mean temperature anomaly of 1.1°C above normal for the year (with the respect to the 1951–80 mean). Nationally averaged temperatures have been at or above normal for the last 11 consecutive years, and 2003 ranked as the sixth warmest since nationwide records began in 1948. Canadian temperatures have shown pronounced variability over the 56-yr record of countrywide measurements (Fig. 6.1), but overall there has been a long-term surface warming trend of +1.1°C. The highest annual nationwide temperature anomaly of +2.5°C occurred in 1998, which was by far the warmest year over the period of record. Of the last 6 yr (1998–2003), 5 have been in the top 10 warmest, with the only exception being 2002. On a seasonal basis, the summer of 2003 was the fourth warmest, and the 11th consecutive warmer-than-average summer. In fact, all four seasons had above-normal temperatures in 2003, with warmer-than-average conditions in 25 of the last 26 seasons.

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