EARTH’S ICE
Earth’s Ice

Accelerated shrinking of mountain glaciers on every continent, rapid reduction of Arctic sea-ice, disintegration of floating ice shelves, and increased melt rates of Earth’s three Ice Sheets—Greenland, West Antarctic, and East Antarctic—provide compelling evidence of our changing climate.
the well-being of approximately one-sixth of the world’s population who depend on glacier ice and seasonal snow for their water resources during dry seasons (WGMS 2008b).

Documentation of this trend has been building for the last century and studies of glaciers and ice caps are becoming more sophisticated with new satellite-based observation technologies and attempts to distinguish glacier responses to multiple variables (WGMS 2008a, WGMS 2008b, Braithwaite 2009). Evidence from increasing loss rates is becoming stronger. In the European Alps, for instance, overall glacial volume reduced by about one per cent per year from 1975 to 2000 and between two and three per cent since the turn of the millennium (Haebert et al. 2007).

Data from the World Glacier Monitoring Service track 30 reference glaciers in nine mountain ranges and document strongly accelerating loss of glacier mass. Since the year 2000, the mean loss rate of these 30 reference glaciers has increased to about twice the loss rates observed during the two decades between 1980 and 1999 (Zemp et al. 2009). The previous record loss in 1998 has been exceeded already three times—in 2003, 2004 and 2006—and the new record loss in 2006 is almost double that of the previous record loss in 1998. The mean annual loss for the decade 1996-2005 is more than twice the value measured between 1986 and 1995 and more than four times that of the period 1976-1985. Certain regions such as southern Alaska suffer from significantly higher losses (Larsen et al. 2007). Positive feedback mechanisms such as albedo change due to dark dust and collapse around glacier peripheries now appear to play an increasingly important role, enhancing mass loss beyond pure climate forcing (WGMS 2008a, WGMS 2008b, Oerlemans et al. 2009).

Among those glaciers losing the most volume in the record year of 2006, Norway’s Breiddalblikkbrae thinned by more than 3 metres in the decade 1996-2005 is more than twice the value measured between 1986 and 1995 and more than four times that of the period 1976-1985. Certain regions such as southern Alaska suffer from significantly higher losses (Larsen et al. 2007). Positive feedback mechanisms such as albedo change due to dark dust and collapse around glacier peripheries now appear to play an increasingly important role, enhancing mass loss beyond pure climate forcing (WGMS 2008a, WGMS 2008b, Oerlemans et al. 2009).

Evidence of glacier loss has been documented on every continent using different methods to measure rates of change. In 1894, the entire area of glaciers in the Pyrenees was mapped and measured for the first time, with the Spanish portion covering 1779 hectares. Measurements were not taken again until 1982, when the area of Spanish Pyrenean glaciers had shrunk to 595 hectares. In 1993, only 468 glacier-covered hectares were measurable and in 2003, only 277 hectares remained (ERHIN 2009). Measurements from 2008 showed glacier extent covering only 260 hectares in the Spanish Pyrenees, with the researchers suggesting that if current trends continue, glaciers will disappear from the Pyrenees by 2050 (González et al. 2008). Most ice caps and glaciers in the mountains of tropical Africa are expected to disappear by 2030 (Eggermont et al. 2007, Hastenrath 2009). Loss

### Table 2.1: Decline of Pyrenean glaciers 1894-2008

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### Numbers of glaciers and ice banks

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<td><strong>TOTAL</strong></td>
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![Figure 2.1: Mean cumulative specific mass balance of indicated glaciers](source: WGMS 2008a)
of permanent ice from Africa’s mountains will have profound effects on surrounding ecosystems, as well as the hydrology and temperature regime of Africa’s unique highland cold-water lakes. Efforts have begun to document the baseline climatic, environmental, and biological conditions in Africa’s mountains to evaluate future changes. Sediments accumulating on the bottom of highland glacial lakes have chronicled the history of central African climate and environmental dynamics, producing the historical perspective needed for resource conservation and responsible adaptation. Surveys of lake sediments in the Rwenzori Mountains show that recent glacier recession started around 1880, broadly coinciding in timing with declining East African rainfall. The data do not show glacial expansion coinciding with the initiation of this wet phase in the early 19th century, highlighting the complexity of the relationship between tropical glaciers and climate (Eggermont et al. 2007).

Repeat photography of some of the earliest glacier images from southern South America reveals drastic, widespread glacier recession in northwestern Patagonia between 38° and 45°S. Linear trends in regionally-averaged annual and seasonal temperature and precipitation records indicate substantial warming and decreasing precipitation over the 1912–2002 interval. Regionally-averaged mean annual stream flow records east of the Andes mountains show a highly significant negative correlation with the regional temperature series. Given the major socio-economic importance of rivers and glaciers in this area, potential impacts of the future warmer and drier climates projected for this region will be considerable (Moore et al. 2009).

Ice cores collected in 2006 from Naimona’nyi Glacier in the Himalaya of the Tibetan Plateau lack distinctive marker horizons, suggesting no net accumulation of ice mass since at least 1950. Naimona’nyi is the highest glacier documented to be losing mass annually, suggesting the possibility of similar mass loss on other high-elevation glaciers in low and mid-latitudes under a warmer Earth scenario. If climatic conditions dominating the mass balance of Naimona’nyi extend to other glaciers in the region, the implications for water resources could be serious as these glaciers feed the headwaters of the Indus, Ganges, and Brahmaputra Rivers that sustain one of the world’s most populous regions (Kehrwald et al. 2008).

In the Himalaya particularly, glacier loss increases the threat of glacier lake outburst floods. Often, mountain glaciers leave a front moraine at their former terminus that can contain the glacier’s melting run-off in a pro-glacial lake. Reservoirs for hydroelectric facilities may have a similar configuration. When a moraine or other type of barrier is breached, the full contents of the lake may descend through the downstream valley as a torrent. The breach can occur because the lake has filled too much, high winds have forced water over the barrier, or a large wave results from sudden collapse of ice at the glacier front or sidewall debris. The result can tear out bottomland, forests, settlements, and hydroelectric power installations very quickly (Chaudhary and Aryal 2009).

Himalayan glaciers are retreating at rates between 10 and 60 metres per year. The terminus of most high valley glaciers in Bhutan, Nepal, and neighbouring parts of China are retreating very fast. Vertical shifts over the last fifty years of 100 metres have been recorded and retreat rates of 30 metres per year have become common. Particular situations with glacier lake outburst flood potential are under observation: These include Nepal’s Lake Imja Tsho in the Khumbu-Everest region—where the Imja glacier is retreating at 74 metres per year, and Bhutan’s Pho Chu Basin where
ARCTIC ICE

2009 Arctic sea-ice extent (area of ocean with at least 15 per cent sea-ice) compared to recent years. Source: NSIDC 2009a

As the melt season of 2009 began, the Arctic Ocean was covered mostly by first-year ice, which formed since September 2008, and second-year ice, which formed during the winter of 2007 to 2008. First-year ice in particular is thinner and prone to melt more quickly than thicker multi-year ice. In 2009, ice older than two years accounted for less than 10 per cent of the ice cover at the end of February (NSIDC 2009a). This is quite a significant decline considering that only a decade ago, older ice on average accounted for 30 per cent the total sea-ice cover at the same time of the year. Ultimately, thinner and more vulnerable Arctic sea-ice has profound implications for the global climate system, as ice cover serves to naturally cool air and water masses, and plays a key role in ocean circulation and reflecting solar radiation back into space.

Two ocean circulation patterns dominate the Arctic Ocean: The Transpolar Drift moves water and ice from the region of the East Siberian Sea along the north of Eurasia and over the North Pole to drain into the deep Fram Strait between Greenland and Svalbard. The Beaufort Gyre circles between the North Pole and the coast of northwestern Canada and Alaska, rotating in a clockwise direction and fostering the growth of multi-year ice as floes circle for many years.

ARCTIC SEA-ICE EXTENT

In 2007, the sea-ice in the Arctic Ocean shrunk to its smallest extent on record, 24 per cent less than the previous record set in 2005 and 34 per cent less than the average minimum extent over 1970-2000 (ESA 2007, Comiso et al. 2008, Stroeve et al. 2008). The minimum sea-ice cover of 2007 extended over 4.52 million square kilometres of the Arctic Ocean (NSIDC 2009a). This is clear evidence of a phenomenon of importance on a planetary scale forced by global warming and caused mainly by an Earth System energy imbalance due to GHG concentrations increasing in the atmosphere (IPY 2009).

Box 2.1: International Polar Year

From March 1, 2007 until February 25, 2009 over 10,000 scientists from 60 nations participated in facets of an international multidisciplinary research collaboration known as the International Polar Year (IPY). The IPY’s coordination and integration of ongoing research projects, as well as exploiting the opportunity to fill in scientific gaps, is attempting to fill the demand for up-to-date scientific interpretations of how climate in the Arctic and Antarctic is changing. As a group, IPY scientists made a statement about the record low sea-ice extent in the Arctic:

“Our main conclusions so far indicate that there is a very low probability that Arctic sea ice will ever recover. As predicted by all IPCC models, Arctic sea ice is more likely to disappear in summer in the near future. However it seems like this is going to happen much sooner than models predicted, as pointed out by recent observations and data reanalysis undertaken during IPY and the Damocles Integrated Project. The entire Arctic system is evolving to a new super interglacial stage seasonally ice free, and this will have profound consequences for all the elements of the Arctic cryosphere, marine and terrestrial ecosystems and human activities. Both the atmosphere and the ocean circulation and stratification (ventilation) will also be affected. This raises a critical set of issues, with many important implications potentially able to speed up melting of the Greenland ice sheet, accelerating the rise in sea-levels and slowing down the world ocean conveyor belt. That would also have a lot of consequences on the ocean carbon sink and ocean acidification.”

Source: IPY 2009
During the last few decades of the 20th century, the positive phase of the Northern Annular Mode (NAM)—an encompassing category that includes Arctic Oscillation and North Atlantic Oscillation states—produced conditions that strengthened Arctic Ocean winds transporting ice away from the Alaskan and Siberian coasts via the Transpolar Drift and flushing large amounts out of the Arctic Basin through the Fram Strait and into the North Atlantic (Serreze et al. 2007). The Transpolar Drift seemed to veer powerfully over the Pole and pick up more ice off the northern edge of the Beaufort Gyre for years, exporting multi-year ice before it could return to the Canada Basin and Beaufort Sea for another annual accumulation of additional ice. By the beginning of the 21st century, the NAM had returned to a more neutral state and multi-year ice accumulated again in the Arctic Basin. However in 2007, positive NAM conditions prevailed over the summer and once again multi-year ice continued to return to the Canada Basin and Beaufort Sea for another annual accumulation of additional ice. The Beaufort Gyre contains significant amounts of fresh water within its ice floes, but also within its circulating water column. Since the 1990s the Beaufort Gyre has reduced in surface area but gained up to 1,000 square kilometres of additional fresh water since the 2000s began by tightening and accelerating its circulation pattern (Proshutinsky et al. 2009). Large amounts of fresh water from the Pacific Ocean, precipitation, ice melt, and discharge from major river systems including the Ob, Yenisey, Lena of Russia and the Mackenzie of Canada. Scientists assumed that Arctic fresh water flowed from the basin in balance with the input from the various sources until observations showed large discrepancies between the two estimates. More recently, researchers suggest that fresh water is stored within Arctic circulation systems under certain conditions and is then released when those conditions dissipate (Proshutinsky et al. 2007). The Transpolar Drift seemed to veer powerfully over the Pole and pick up more ice off the northern edge of the Beaufort Gyre for years, exporting multi-year ice before it could return to the Canada Basin and Beaufort Sea for another annual accumulation of additional ice. By the beginning of the 21st century, the NAM had returned to a more neutral state and multi-year ice accumulated again in the Arctic Basin. However in 2007, positive NAM conditions prevailed over the summer and once again multi-year ice continued to drain from the Arctic Basin (Maslanik et al. 2007, Serreze et al. 2007, Kwok et al. 2009, NSIDC 2009a). Based on sea-ice age data from researchers at the University of Colorado, during the winter of 2008/2009, 390,000 square kilometres of second-year ice and 190,000 square kilometres of older (more than two years old) ice moved out of the Arctic (NSIDC 2009a).

Researchers recognize the gradual long-term warming over the last 30 years, mostly characterized by milder winter freezing seasons and longer summer melting seasons, evidencing strong reflectivity or positive albedo feedback effects. Less ice means more open water exposed to shortwave solar radiation that would be absorbed and transformed into heat. Strong positive feedback accelerates the melting of Arctic sea-ice, largely due to the sharp contrast of the high albedo for sea-ice areas covered with snow that reflects 80 per cent of the incoming solar radiation back into space, in contrast with the very low albedo of the ocean that reflects only 20 per cent of the solar radiation, absorbing the other 80 per cent (Graversen et al. 2008, Dmitrenko et al. 2008).

Natural variability in atmospheric and ocean circulation patterns combined with radiative forcing to shrink the 2007 ice extent so much. The western Arctic Ocean in 2007, observations estimate total summertime cloud cover decreased by 16 per cent from 2006 to 2007. Over three months of 24 hour sunlight under clear skies, the total radiative forcing warmed the surface ocean by 2.4 degrees Celsius, enhancing basal ice melt. Both an increase in air temperatures and a decrease in relative humidity, associated with the persistent clockwise atmospheric circulation pattern, explain the reduced cloudiness (Kay et al. 2008).

Major efforts since 2002 to document the nature of the Beaufort Gyre have reported significant differences between the climatology of the 1990s and the observed phenomenon characterizing post-2003 conditions. The Beaufort Gyre contains significant amounts of fresh water within its ice floes, but also within its circulating water column. Since the 1990s the Gyre has reduced in surface area but gained up to 1,000 square kilometres of additional fresh water since the 2000s began by tightening and accelerating its circulation pattern (Proshutinsky et al. 2009). Freshwater sources in the Arctic include flow from the Pacific Ocean, precipitation, ice melt, and discharge from major river systems including the Ob, Yenisey, Lena of Russia and the Mackenzie of Canada. Scientists assumed that Arctic fresh water flowed from the basin in balance with the input from the various sources until observations showed large discrepancies between the two estimates. More recently, researchers suggest that fresh water is stored within Arctic circulation systems under certain conditions and is then released when those conditions dissipate (Proshutinsky et al. 2007).
2008, McPhee et al. 2009, Proshutinsky et al. 2009). Scientists from the Norwegian Polar Institute warn that fresh water is piling up in the Arctic Ocean and that a change in the dominant wind direction could release the largest amount of fresh water through Fram Strait ever recorded (NPI 2009, Holfort et al. 2009).

Before the 2007 summer, most models for seasonal ice loss envisioned an ice-free September for the Arctic Ocean in the waning years of the 21st century (Serreze et al. 2006, Boï et al. 2009). The plummeting sea-ice extent of 2007 demanded new analyses and suggested new trends. Researchers who track the growth and melt of polar ice found the longterm outlook “disturbing”, particularly because all the models used for the IPCC AR4 underestimated the timing of Arctic ice loss (Stroeve et al. 2007, Stroeve et al. 2008). They suggest this may be due to an assumption of sea-ice thickness in the models greater than existed in reality (Stroeve et al. 2008). A reconsideration of the trends led to speculations that the Arctic Ocean may be ice-free in September by 2030.

The continuing sparse ice extent recorded in September 2008 spurred further analysis: At current rates of coverage, more than 60 per cent of the Arctic Ocean area is open to increased solar irradiation at the end of summer and temperatures in the Arctic autumn now reach 5-6 degrees Celsius above the climatological norm (Wang and Overland 2009, Overland 2009). From examination of models that most closely match the observation of summer Arctic sea-ice loss including 2007 and 2008, these researchers suggest that the Arctic could be virtually ice-free in September of 2037 (Wang and Overland 2008). Furthermore, they posit that with summers like 2007, a nearly ice-free September by 2028 is well within the realm of possibility.

The confidence behind these projections of rapidly decreasing Arctic summer sea-ice is based in those same models: Some indicate rapid ice cover decrease once the areal extent of the ice cover shrinks to vulnerable dimensions (Serreze and Francis 2006, Stroeve et al. 2008, Wang and Overland 2009).

Some Arctic sea-ice loss simulations suggest a different sequence of possible future events: A gradual transition to a seasonally ice-free Arctic Ocean and then a shift to a year-round ice-free state (Delworth et al. 2008, Delworth et al. 2006). Earlier models showed this possible shift to year-round ice-free conditions could happen either gradually or abruptly (Winton 2006). New research supports a seasonally ice-free Arctic with some stability: The thermodynamic effects of sea-ice mitigate the possibility of sudden ice loss when the Arctic Ocean is ice covered during a sufficiently large fraction of the year. These results suggest that critical threshold behaviour is unlikely as perennial sea-ice conditions develop to seasonally ice-free conditions. However, these models still allow that a critical threshold associated with the sudden loss of the remaining wintertime-only sea-ice cover may exist (Eisenman and Wettlaufer 2009).

From September of 2006 until January of 2008, the research schooner Tara—sponsored by the European Union Programme: Developing Arctic Modeling and Observing Capabilities for Long-term Environmental Studies (DAMOCLES)—travelled on the Transpolar Drift to reproduce the 1894-1896 Fram expedition led by Fridtjof Nansen. Tara drifted closer to the North Pole than Fram had, and surprisingly Tara completed the transect from the Laptev Sea to the Fram Strait in 15 months while the drift carried the Fram that distance in 3 years. In September of 2007, the Russian vessel Akademik Fedorov deployed a drifting station near the Severnaya Zemlya Russian islands. That drifting station was recovered near Svalbard ten months later, confirming the acceleration of the transpolar drift as also observed by Tara (IPY 2009). A series of buoys dropped on Transpolar Drift ice in 2001, 2004, and 2007 followed through on research begun in 1991 that verified the ice travelling through the drift has become first- and second-year ice in recent years while the earlier observations showed older ice was previously common in the system (Haas et al. 2008).

The Canadian Arctic Archipelago (CAA) is also changing rapidly. In a study following data from 1979-2008, the average September total sea-ice

Box 2.2: Implications of sea-ice loss

The implications of so little multi-year ice in the Arctic are now being investigated. First-year ice melts more quickly, so larger areas of open water will be exposed to solar radiation earlier in the year, which will increase both sea and atmospheric temperatures. The larger heat transfer from the ocean to the atmosphere—the maritime effect—will help moderate autumn and winter cold temperatures. As ice retreats from shorelines, winds gain a longer fetch over open water, resulting in stronger waves and increased shore erosion.

Accelerated sea-ice loss will not only affect the Arctic Ocean coast. The rapid retreat of Arctic sea-ice could accelerate rapid warming 1,500 kilometres inland throughout Alaska, Canada, and Russia. During rapid ice retreat, the rate of inland warming could be more than three times that previously suggested by global climate models.

Such drastic changes in climate will affect ecosystems and the human populations that depend on them. While higher temperatures are radically changing the environment in the North, they also will thaw out extensive expanses of permafrost, defined as earth that remains frozen for two or more consecutive years. The more apparent effects will include damaged infrastructure as roads, pipelines, and foundations collapse, as well as ‘drunken forests’ that result from altered rooting conditions. More serious complications result from the potential release of methane and carbon dioxide that are currently frozen in Arctic soils. The expected rapid soil thaw could also produce a talik—a layer of permanently unfrozen soil sandwiched between the seasonally frozen layer above and the perennially frozen layer below—which in turn creates a more rapid heat build-up in the soil, further accelerating the longterm thaw and release of carbon dioxide (Lawrence et al. 2009, UNEP 2008c, Serreze et al. 2007, Jones et al. 2009, Jones et al. 2008, Mars and Houseknecht 2007).
area within the CAA has decreased by 8.7 per cent each decade, while the melt season duration is increasing significantly at 7 days per decade. The longest melt season of the full thirty years lasted 129 days in 2008. The CAA is on the receiving end of the multi-year ice delivery from the interactions of the Transpolar Drift and the Beaufort Gyre, but even there the average September multi-year ice area is decreasing by 6.4 per cent per decade. The Northwest Passage, touted as a future shortcut between the North Atlantic and the Pacific, will continue to be susceptible to multi-year ice blocking the Western Parry Channel region as the transition to a sea-ice free Arctic summer continues, limiting the dependability of transiting through the CAA (Howell et al. 2009).

In the early 20th century, explorers of Canada’s Ellesmere Island described a glacial front skirting the island’s northern coast. Modern glaciologists have deduced that this ice front was likely a continuous ice shelf covering some 89,000 square kilometres. By the 1950s, much of that ice had disintegrated. Retreating glaciers which formerly fed the vast amalgamated shelf differentiated and lost contact with each other. That retreat and differentiation, together with the reduced protection once sea-ice loss took effect, contributed to the now almost complete disintegration of Ellesmere Island ice shelves (England et al. 2008, Mueller et al. 2008, Scott 2008).

The loss of sea-ice in the Arctic Ocean will have serious repercussions as feedbacks from temperature increases, altered seasons, and shifting circulation patterns cascade through Arctic biophysical systems. But the loss of Arctic Ocean sea-ice will not directly lead to any significant sea-level rise because all the ice is already floating. Ice shelves on surrounding coastlines and glaciers that reach inland and deliver ice to the oceans will experience additional melt from the warmer temperatures (England et al. 2008). Inland and outlet glaciers will continue to contribute to sea-level rise. Observations over the past decades show a rapid acceleration of several outlet glaciers in Greenland and Antarctica.

OUTLET GLACIERS IN TRANSITION

Among the various oceanographic, hydrological, atmospheric, and ecological consequences of changes in the volume of the Earth’s land ice, the forecasting of future sea level stands as arguably the most globally significant. One process by which sea level is increased is by the addition of new water mass from land ice. This transfer can occur by melting of ice from direct climatological forcing, but also by the flow of glacier ice mass into oceans and calving of icebergs into the ocean—aspects of glacier dynamics. Glacier dynamics can produce extremely rapid increases in sea level because increasing glacier flow and iceberg calving do not track increasing temperature in a simple way, but sometimes respond non-linearly and irreversibly to climate inputs. Past dynamic contributions to sea level have long been hypothesized from geologic evidence, while the possibility of rapid dynamic response of ice sheets to climate change has been under consideration since the 1970s. Most research on rapid dynamic changes since that time, including rapid iceberg discharge, has been conducted on glaciers and ice caps; however, somewhat in the past decade but especially since the IPCC AR4, research on dynamics of ice sheets, as well as glacier and ice cap dynamics, has increased sharply (Zwally et al. 2002, Pfeffer 2007, Benn et al. 2007, Howat et al. 2008, Briner et al. 2009). Understanding of the mechanisms and controls on rapid dynamic-forced changes in glacier and ice sheet contributions to sea level is now among the most urgently pursued goals in glaciology and sea-level investigations. The notable absence of predictions of a dynamic-forced component of sea-level rise from the IPCC AR4 made their sea-level predictions a very conservative lower-bound estimate (IPCC 2007b).

Two main hypotheses guide current research to explain the acceleration of outlet glaciers in Greenland, Antarctica, and at the marine boundaries of other glaciers and ice caps. The first suggests that dynamic changes result from processes that act to destabilize marine-ending termini and disrupt force balances that persist up the glacier. This destabilization then leads to faster ice flow and thinning that propagates rapidly up-glacier and leads to further retreat (Pfeffer 2007, Sole et al. 2008). The second hypothesis is that warmer air temperatures accelerate sliding by increasing the amount of surface melt. Some fraction of surface water may percolate through the ice mass and, once it reaches the glacier bed, increases basal lubrication and the rate at which ice slides over its bed. This leads to glacier acceleration, thinning, and terminus retreat. This mechanism would behave similarly on both land and marine terminating outlet glaciers (Parizek and Alley 2005, Sole et al. 2008).

GREENLAND ICE

The recent marked retreat, thinning, and acceleration of most of Greenland’s outlet glaciers south of 70° N has increased concerns over contributions from the Greenland Ice Sheet to future sea-level rise (Howat et al. 2005). These rapid changes seem to be parallel to the warming trend in Greenland, the mechanisms are poorly understood.

An analysis of a large sample of southern Greenland Ice Sheet marine- and land-terminating outlet glacier thinning rates showed that more than 75 per cent of marine-terminating outlet glaciers are thinning significantly more than their land-terminating counterparts. There was a dramatic
increase in almost all marine outlet glacier thinning rates from 1993 to 2006, when the documentation ended, suggesting a widespread forcing mechanism. These findings suggest that a change in a controlling mechanism specific to the thinning rates of marine-terminating outlet glaciers occurred in the late 1990s and that this change did not affect thinning rates of land-terminating outlet glaciers (Sole et al. 2008).

A study of Helheim Glacier, a large outlet glacier on Greenland’s eastern coast, used an ice flow model to reproduce the changes documented for the glacier’s recent dynamics. The researchers found the ice acceleration, thinning, and retreat began at the calving terminus and then propagated upstream along the glacier. They could not detect any relationships between surface ice melt or drainage and any subsequent changes in ice dynamics. They concluded that the changes were unlikely to be caused by basal lubrication through surface melt propagating to the glacier bed. While the researchers confirmed that tidewater outlet glaciers adjust extremely rapidly to changing boundary conditions at the terminus, they could not determine any boundary condition change that initiated the terminus’ instability and concluded that recent rates of mass loss in Greenland’s outlet glaciers are transient and should not be extrapolated into the future (Nick et al. 2009).

Another study focused on western Greenland’s Jakobshavn Isbrae responsible for draining 7 per cent of the ice sheet’s area, which switched from slow thickening to rapid thinning in 1997 and suddenly doubled its velocity. Here, the change in glacier dynamics is also attributed to destabilization of the glacier terminus, but the researchers are able to attribute that to warmer ocean water delivered to the fjord. However, these researchers were also able to detect short-term and less significant fluctuations in Jakobshavn Isbrae’s behaviour that could be attributed to meltwater drainage events (Holland et al. 2008).

They present hydrographic data documenting a sudden increase in subsurface ocean temperature along the entire west coast of Greenland in the 1990s that reached Jakobshavn Isbrae’s fjord in 1997. The researchers trace the warm flow back to the east of Greenland where the subpolar gyre that rotates counter clockwise south of Iceland scoops warmer water from an extension of the Gulf Stream and directs it back west and south around the tip of southern Greenland. In the early 1990s the North Atlantic Oscillation atmospheric pattern switched phase and drove the subpolar gyre closer to the Greenland shore, accelerating the flow of the warm water around the tip and up the western shore, where it eventually reached the Jakobshavn Isbrae fjord (Holland et al. 2008). The delivery of warm water to the base of Jakobshavn Isbrae’s fjord persisted through 2007 and the retreat continued at least through 2008, with shorter term fluctuations affected by surface melt permeating through the ice mass (Holland et al. 2008, Box et al. 2009). Whether this pulse of warm water from the subpolar gyre also affected Helheim and other marine outlet glaciers in Greenland will have to be investigated.

Such studies not only illuminate the dynamics of outlet glaciers in a changing environment and subject to a variety of forcings, they also help us understand the significance of particular topographical configurations beneath ice that certainly affect current phenomena and could play a strong role in future events. Both Helheim and Jakobshavn occupy deep valleys that extend far into Greenland’s inland territory. The possibility remains, for these and similarly configured outlet glaciers, that should they lose their ice plugs they would act as drainage outlets for Greenland’s interior meltwater. Given the many interacting variables affecting the Earth’s ice in a changing climate, the future behaviour of these large outlet glaciers remains unpredictable (Holland et al. 2008, Nick et al. 2009).

Many other outlet glaciers in Greenland are in retreat from disturbance at terminus and because of meltwater permeating their mass. In 2008, researchers reported on one of the thousands of melt-water lakes that now form on Greenland each summer. The four-kilometre-wide expanse of water that formed in 2006 completely drained into the icy depths in 90 minutes, at a flow rate greater than Niagara Falls (Joughin et al. 2008, Das et al. 2008). The latest documentation has shown that this particular melt drainage event fed into the Jakobshavn Basin behind the glacier terminus (Mottram et al. 2009).

The nature of Greenland Ice Sheet surface melt is also under examination and it seems to be accelerating: A time series of Greenland surface melt extent, frequency, and onset has been updated to include data from 1973 to 2007, when the documentation ended. The seasonal melt departure, the sum from 1 June to 31 August of the departure from average of each day’s melt extent, is a new metric used to describe the amount of melt. Results show a large increase in melt in summer 2007, 60 per cent more than the previous high in 1998. During summer 2007, some locations south of 70°N had as many as 50 more days of melt than average. Melt occurred as much as 30 days earlier than average. The seasonal melt departure is shown to be significantly related to coastal temperatures as monitored by meteorological stations, although 2007 had more melt than might be expected, based on the summer temperature record (Mote 2007).

ANTARCTIC ICE

The very high average elevation, about 2,300 metres above sea level, of the Antarctic Ice Sheet and continuous latitudinal ring of open ocean separating Antarctica from other landmasses isolates the ice sheet from warmer latitudes to the north. Prevailing westerly winds encircling Antarctica match a circulation pattern in the Southern Ocean, the Antarctic Circumpolar Current (ACC), which is the Earth’s fastest moving current and is only constrained as it passes from the Pacific to the Atlantic through the Drake Passage. Non-synchronous and multidecadal influences—from the westerlies, the ACC, pressure systems that build over the Southern Ocean, and the amount of fresh water draining from the continent—all affect fluctuations of Antarctica’s ice (Mayewski et al. 2009).
Parts of Antarctica are also losing ice, particularly from the West Antarctic Ice Sheet. Researchers estimate that loss of ice from West Antarctica increased by 60 per cent in the decade to 2006. Ice loss from the Antarctic Peninsula, which extends from West Antarctica towards South America, increased by 140 per cent. The processes affecting the peninsula involve accelerating glacier flows caused by both warmer air and higher ocean temperatures (Rignot et al. 2008). An additional factor in West Antarctica and the Antarctic Peninsula that could undermine the integrity of the great ice sheets is the recent disappearance of a number of ice shelves that build along those shores.

Box 2.3: Relationships between stratospheric ozone and climate change

Integrating the effects of changing stratospheric ozone concentrations with climate models remains a challenge for Earth System scientists. However, new research and experimentation are revealing the wide range of influence that stratospheric ozone depletion has on temperatures in the upper troposphere that can propagate downward. In the troposphere, and reaching to the Earth’s surface, this influence may reach to affecting the speed of the Southern Westerlies, the strength of cyclonic circulation in the Southern Ocean, the extent of Antarctic sea-ice, and the possibility of upwelling that releases carbon dioxide from deep ocean reservoirs. Stratospheric ozone depletion is partly responsible for masking expected warmth in Antarctica, and successful ozone recovery will lead to the projected increase in Antarctic temperatures.

These shelves are immense—the Ross ice shelf is the largest and is slightly smaller than Spain. The shelves are already floating on the ocean so their loss does not add to sea-level rise. But they are attached to the ice sheets and act as buttresses (BAS 2008). When they go, the ice sheets may accelerate out into the ocean and that does displace the water. Ice shelves also act as buffer areas between the changes in temperature and winds over open waters of the Southern Ocean and the more subdued weather systems of Antarctica’s interior.

A large part of the 13,000 square kilometre Wilkins Ice Shelf, between 70° and 74°W along the Antarctic Peninsula, collapsed in February 2008 (Braun et al. 2008). At that time the British Antarctic Survey said the shelf was in imminent danger of disintegration because it seemed to be stabilized only by a slim ice bridge that extended between two islands (BAS 2008). Finally, in early April 2009, that ice bridge broke and throughout the Antarctic winter the shelf has been sheering into huge silvered bergs that are slowly moving away from the mainland (ESA 2009). The collapse of the Wilkins Ice Shelf will not directly lead to sea-level rise but the event serves as a dire warning: Ice shelves have the potential to become unstable on very short timescales. The collapse of the Wilkins Ice Shelf and its predecessor, the Larsen Ice Shelf which collapsed in 2002, show that, like rapid dynamic response of outlet glaciers, ice shelves can undergo rapid change (Turner et al. 2009).

Weather and climate data from Antarctica are difficult to gather because of the size of the region, the logistical difficulties in getting to many areas, and the physical difficulties of working on a continent of ice that is dark and isolated for at least six months every year. As a result, lack of data still remains a significant problem for researchers of Antarctic science. Starting in 1957’s International Geophysical Year, data of differing qualities and coverage have been gathered by manned stations, automated weather stations, and satellites. Even today with 42 ground stations in Antarctica, the distribution concentrates along the coasts and paralleling the Transantarctic Mountains to the south of the Ross Ice Shelf. Ground data from the vast interior of the East Antarctic Ice Sheet are still sparse (Steig et al. 2009).

In recent decades, traditional assessments of Antarctic temperature change noted the contrast between strong warming around the Antarctic Peninsula and slight cooling of Antarctica’s interior (Monaghan et al. 2008). This cooling pattern of the interior has been attributed to an increased strength of the circumpolar westerlies reacting to the expansion of the southern subtropical zone moving out from lower latitudes and associated with the depletion of ozone in the stratosphere at those polar latitudes. Without a strong ozone layer at the lower boundary of the stratosphere, the colder stratospheric circulation can propagate downwards to the troposphere and affect surface temperatures over Antarctica and as far north as Patagonia (Thompson and Solomon 2002).

Recent findings show that significant warming extends well to the south of the Antarctic Peninsula to cover most of West Antarctica, an area of warming much larger than previously reported. West Antarctic warming exceeded 0.1°C per decade over the past 50 years, and has been most marked during winter and spring. The whole continent’s average near-surface temperature trend is warming, although this is offset somewhat by East Antarctic cooling in autumn (Monaghan et al. 2008, Steig et al. 2009). These trends appear unrelated to changes in the westerlies; instead, analysis attributes the warming to regional changes in atmospheric circulation and associated changes in sea surface temperature and sea-ice (Steig et al. 2009).

Studies of satellite data covering 1987–2006 track how melt is advancing farther inland from the Antarctic coast over this period. Evidence suggests that melt is reaching to higher altitudes and is accelerating on the continent’s largest ice shelf (Tedesco et al. 2007).
when melting began in the different regions with the first evidence along the Peninsula, east from the Peninsula to about 30°E, and then west to the Ross Ice Shelf with detectable melt by 1990.

In contrast to the dramatic decrease in Arctic sea-ice cover, the total area of Antarctic sea-ice has been increasing since the 1970s. At its maximum near the end of the Southern Hemisphere’s winter in September, Antarctic sea-ice covers an area of 150,000 square kilometres or more. At maximum extent, southern sea-ice accumulates off the Ross Ice Shelf in the Ross Sea and clots into a rotating mass in the Ross Gyre. Another expansive accumulation grows to the east of the Antarctic Peninsula, in the Weddell Sea.

The Southern Ocean and associated air masses and cryosphere have undergone increased perturbation during recent decades. Ocean station and drifting float observations have revealed rising temperatures in the upper 3,000 metres. Salinity has declined in waters at intermediate depth and the decline may be speeding up in the sparsely sampled latitudes nearest the pole. Sea-ice area increased from 1979 to 1998, particularly in the Ross Sea, while a decline in ice extent since the early 1970s has been led by the Amundsen–Bellingshausen sector. Fresher waters with lower oxygen isotope content on the Pacific–Antarctic continental shelf are consistent with increased melting of continental ice. New bottom water has become colder and less salty downcurrent from that region, but generally warmer in the Weddell Sea. Many ice shelves have retreated or thinned, but others have grown and no trend is apparent in the large iceberg calving rate. Research suggests that ice dynamics in Antarctica are in a state of flux—learning how they are responding to environmental change offers one of the most exciting challenges facing Earth System scientists over the next decade and more (Mayewski et al. 2009).

Many observed Antarctic ice dynamics, especially the increase in sea-ice, have also been linked to the effects of the stratospheric ozone loss (Thompson and Solomon 2002). The effects of the ozone hole extend down through the atmosphere during the summer and autumn so that the greatest increase in surface winds over the Southern Ocean has been during the autumn. However, over approximately the next half century there is expected to be a return to the pre-ozone hole concentrations of ozone, which is expected to bring even warmer temperatures and more dynamic ice conditions (Turner et al. 2009).

Influences on Antarctic climate are becoming more clearly understood, as are the influences that climate has on the whole region. The Earth’s ice is responding to warmer temperatures and to a number of complex related processes. Melt from mountain glaciers and ice caps and the Antarctic and Greenland Ice Sheets will continue to contribute to sea-level rise. The question is how much melt will the different sources contribute—and over how long a period?

Figure 2.7: Antarctic temperature trends and sea-ice cover

Image shows an overlay of Antarctica’s ongoing warming temperature trends (between 1981-2007) and 4 September 2009 sea-ice cover (per cent of total area). Source: NASA 2007, NSIDC 2009b