Recent Changes in High-Latitude Glaciers, Ice Caps, and Ice Sheets

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The glaciers and ice sheets of the world contain enough ice to raise sea level by approximately 70 meters if they were to disappear entirely, and most of this ice is located in the climatically sensitive polar regions. Fortunately changes of this magnitude would probably take many thousands of years to occur, but recent discoveries indicate that these ice masses are responding to changes in today's climate more rapidly than previously thought. These responses are likely to be of great societal significance, primarily in terms of their implications for sea level, but also in terms of how their discharge of freshwater, through melting or calving, may impact ocean circulation.

For millions of years, oceans have risen and fallen as the Earth has warmed and cooled, and ice on land has shrunk and grown. Today is no different in that respect, as sea levels have been rising at a rate of nearly 2 mm per year during the last century (Miller and Douglas 2004), and 3 mm yr^{-1} in the last 12 years (Leuliette et al. 2004). What is different today, however, is that tens - perhaps hundreds - of millions of people live in coastal areas that are vulnerable to changes in sea level. Rising seas erode beaches, increase flood potential, and reduce the ability of barrier islands and coastal wetlands to mitigate the effects of major storms and hurricanes. The costs associated with a one-meter rise in sea level are estimated to be in the hundreds of billions of dollars in the

United States alone. The worldwide costs in human terms would be far greater as some vulnerable low-lying coastal regions would become inundated, especially in poorer nations that do not have the resources to deal with such changes. Such considerations are particularly important in light of the fact that a one meter sea level rise is not significantly outside the 0.09 to 0.88 range of predictions for this century (IPCC 2001), and rises of this magnitude have occurred in the past in as little as 20 years (Fairbanks 1989).

While the expansion of the warming oceans is estimated to be about a third of recent sea level rise, (Miller and Douglas 2004) the greatest potential for significantly increasing sea level lies in the Greenland and Antarctic ice sheets. For different reasons, each exhibits characteristics that suggest they are potentially unstable. In Antarctica, large portions of the ice cover rest on a soft bed that lies below sea level, making it vulnerable to runaway retreat. The Greenland ice sheet experiences considerable melt, which has the potential to rapidly accelerate the flow of ice toward the sea. While smaller ice masses, such as the Alaskan Glaciers and the Canadian ice caps, do not have anywhere near the same potential to impact sea level as the vast ice sheets do, many are melting rapidly, posing a significant near-term threat.

To understand how ice sheets and glaciers may contribute to sea level in the next hundred years, it is important to understand what controls the balance of mass of a glacier or ice sheet. Mass balance refers to the difference between those factors that add mass – mainly snow accumulation – and those that remove mass, such as surface melt, melting beneath floating ice, calving and sublimation. These processes are shown schematically for an ice sheet in Figure 1.

As the climate warms, all of the components of mass loss tend to increase, contributing to a shrinking of the glaciers. At the same time, however, amount of snow that falls on the surface also increases, contributing to their growth. For the large ice sheets, it is not so obvious which of these processes will dominate throughout the next century. As a result there is considerable interest in understanding what is happening to the Earth's great ice sheets and high latitude glaciers and ice caps. The last decade has seen tremendous advances in our ability to observe changes in the Earth's ice cover with deployment of new spaceborne and airborne instruments and the advent of key satellite data sets. These observations combined with complementary field activities and modeling efforts continue to provide important new insights into the mechanisms that control mass balance, and they hint at how these processes may behave in the future.

The Antarctic Ice Sheet

In the case of Antarctica (Fig. 2), which contains the equivalent of 61 meters of sea level, the West Antarctic Ice Sheet (WAIS) rests on a soft deformable bed that lies below sea level. As a result, a significant retreat would allow water to fill the ice-bed interface, reducing friction and increasing the tendency of the WAIS (with up to 6 m sea level equivalent) to discharge its ice to the surrounding seas. For this reason, it is much less stable than its east Antarctic counterpart.

More than 4 kilometers thick in some areas, some of this ice is still responding to climate changes of thousands of years ago, and until very recently, it was the prevailing view that the only way ice sheets respond to changes in climate is slowly. However, while changes at the ice sheet interior may take millennia to occur, near the edges, the story is different. Much of Antarctica's perimeter is covered with floating ice shelves or ice tongues, which are susceptible to the effects of a warming atmosphere and ocean, which in turn have important implications further into the ice. This vulnerability was made dramatically apparent in 2002, when in a matter of weeks, much of the Larsen-B ice shelf collapsed (Fig. 3). Prior to its collapse, Larsen B was hundreds of meters thick, and is believed to have existed for more than 12,000 years, yet it disappeared in what can be considered in glaciological terms to be an instant. The collapse of this ice shelf, in and of itself, is not related to changes in sea level, since this was ice that had been floating, but it offers a dramatic example of the sensitivity of this ice cover to its changing environment.

What occurred in the months and year that followed the break-up, however was similarly dramatic and of direct consequence to sea level. Scambos et al. (2004) reported that all of the glaciers that flowed into what was the Larsen B ice shelf, had accelerated, some by as much as a factor of 8. As a result, these glaciers thinned rapidly – one by 38 meters in six months – as they increased their discharge to the sea. At the same time, glaciers that feed the remnants of the Larsen that did not collapse, showed no sign of acceleration.

This experiment of nature helped confirm a disputed hypothesis from several decades earlier that ice shelves act to buttress a glacier and restrain its flow (Thomas 1979). Once that barrier is removed, as was the case with the Larsen B, the buttressing effect is no longer, and the ice accelerates its flow to the sea. This faster flow is not necessarily sustained, however, as over time, these glaciers adjust to their new boundary conditions and reach a new state of equilibrium.

The location of the Larsen-B Ice Shelf on the Antarctic Peninsula is an extreme example, because the peninsula has warmed several degrees Celsius in the later part of the 20th century (Vaughan et al. 2004). This warming is greater than that over the rest of the continent, most of which has experienced cooling in recent decades. Still, we see signs of this behavior of retreat followed by acceleration and thinning elsewhere on the ice sheet, most notably the Thwaites and Pine Island glacier regions that drain into the Amundsen Sea (Thomas et al. 2004). Dubbed the "weak underbelly" of the West Antarctic ice sheet for its potential instability, this area is estimated to contribute as much as 0.13 to 0.24 mm yr^{-1} to sea level (Shepherd et al. 2002 and Thomas et al. 2004 respectively), which is as much as ten percent of the total estimated rate of sea level rise. The reason has been an acceleration of the glaciers that flow into the Amundsen Sea, most likely in response to a weakening (thinning and retreating) of the ice shelf caused by warm ocean currents that are about 0.5°C above freezing (Shepherd et al. 2004). What is happening in this region is not as dramatic as what was observed in the vicinity of the Larsen B ice shelf, but it is of greater consequence, given the magnitude of the sea level contribution and potential instability of the region. If the ice shelves disappear and glacier retreat proceeds further into the basin, these glaciers could continue to accelerate, further increasing their sea level contribution.

While these and other observations suggest that the WAIS is shrinking, the picture is a little more complicated. As a number of the ice sheet's outlet glaciers and ice streams are accelerating, some have slowed and even stopped, most notably the Kamb Ice Stream (formerly Ice Stream C) that feeds into the Ross Ice Shelf. As a result, some areas of the WAIS are growing, and actually slowing the current rate of sea level rise. At the equivalent of about 0.07 mm yr^{-1} of sea level rise (Joughin and Tulaczyk 2002), however, the net growth of these ice streams is not enough to offset the losses observed elsewhere on the WAIS.

In the case of the vast East Antarctic ice sheet, satellite measurements reveal that the ice – apart from that at the edges – is thickening at an rate of 1.8 cm yr^{-1}. The cause of this growth in these areas of East Antarctica is believed to be increased accumulation, which results in an estimated reduction of sea level of 0.12 mm yr^{-1} (Davis et al. 2005). Thus the ongoing battle between growth in Antarctica's interior, and losses at the edges continues, without one process clearly dominating the other.

The Greenland ice sheet

With a total volume of 2.25 km^3 and an average thickness of 1.6 km, the Greenland ice sheet is roughly one tenth the size of the Antarctic ice sheet, and it contains the equivalent of 7 meters of sea level. Unlike Antarctica, however, much of this ice sheet experiences melt. It is this melting, of floating ice shelves and ice tongues around the perimeter, and of snow and ice in the interior, that can create a potentially unstable state of balance in Greenland. This melting has been increasing.

From the period 1979 – 2004, the period for which we have the satellite data that form the basis for determining ice sheet melt extent, the average melt area during the summer months (June, July, and August), increased by 16% (Fig. 4). This increasing melt trend is consistent with the overall warming trend that suggests the Arctic has warmed twice the rate of the Earth as a whole in the past few decades (ACIA 2004). These warm temperatures contribute to the melt increases, and because melting darkens the surface, a positive feedback mechanism is established, whereby the melt process is self-compounding.

Apart from contributing directly to the loss of ice through the runoff of melt water, this melt also has the potential to contribute to ice loss through other, perhaps more substantial, means. Data from the equilibrium line on the western flank of the Greenland ice sheet (the area where net losses from melt and flow are equal to gains from accumulation), indicate that surface melt water penetrates through crevasses or moulins in the ice (Fig. 5) through over a kilometer of ice, where it lubricates the interface between the ice and the bedrock, causing a summertime acceleration (Zwally et al., 2002). This summer acceleration hastens the flow of ice toward the edges of the ice sheet, where it either is discharged to the sea or melts. Over time, this phenomenon can change the shape of an ice sheet, causing a lowering of these regions making them more susceptible to future melt (Parizek and Alley 2004).

Many of Greenland's outlet glaciers are tidewater glaciers that flow directly into the sea, where they terminate with a floating ice tongues that may be up to tens of kilometers in length. These ice tongues experience melt at the surface during the spring and summer months, and from underneath as a result of their contact with relatively warm seawater. As with Antarctica, when these floating tongues retreat or collapse, the associated elimination of their buttressing effect allows the glaciers that feed them to accelerate, causing these glaciers to thin very rapidly in some cases.

Nowhere in Greenland has this been more vividly observed than on the Jakobshavn Isbrae. While observations of many of Greenland's outlet glaciers through the mid-late 1990s showed general thinning, the Jakobshavn ice stream, which at about 7 km yr^{-1} has been one of the fastest glaciers in the world, actually thickened slightly. This thickening appears to be a direct result of a slowing down of the ice stream in the mid 1990s (Joughin et al. 2004). Since, 1997, however, the floating ice tongue began to thin substantially, as air and water temperatures in the vicinity increased (Thomas et al., 2003). This thinning weakened the ice tongue, which, after remaining in a stable location for roughly 50 years began retreating in 2001 at several km each year until reaching its current 2005 location (Fig 4).. The thinning and retreat were accompanied by successive accelerations of the ice stream such that by 2003, the flow rate had nearly doubled, reaching 12.6 km yr^{-1} (Joughin et al., 2005). Associated with these velocity increases, have been rapid ice stream thinning rates of about 15 m yr^{-1} (Krabill et al. 2004) This retreat has continued through 2005 and the total implications on the speed are not yet known, as there are limits to how fast the ice stream can flow. However, the rapid thinning that began in 1997 has propagated inward, as the ice stream continues to lose mass and draw down ice from further upstream and the surrounding vicinity (Thomas et al. 2003). We see similar rapid-thinning in the Kangerdlugssuaq Gletscher on the east coast, which thinned in the late 1990s by more than 10 m yr^{-1} (Thomas et al., 2000).

While what we have observed in Jakobshavn and Kangerdlugssuaq are the more extreme cases, there is evidence that many of Greenland's outlet glaciers are shrinking as a result of flow rates that exceed that which is needed to balance the difference between surface accumulation and ablation (Abdalati et al., 2001). These dynamic effects, along with increasing melt rates, are contributing to the fact that while the mass balance of the Greenland ice sheet's high interior (the accumulation zone) has remained relatively stable or increased some, the margins, where melt occurs (Fig. 4), have shrunk. The net result was an estimated 59 km^3 of ice loss between 1993/4 and 1998/9 (Krabill et al 2004). Between 1997 and 2003, that negative balance is estimated to have increased to 80 km^3 of ice. These represent 0.15 and 0.20 mm of sea level per year respectively (Krabill et al., 2004).

In view of the increasing melt rates, and the links between melt and accelerated ice sheet flow, it is quite realistic to assume that melt regions around the perimeter of the ice sheet will continue to thin, and the phenomena we've been observing in Jakobshavn and Kangerdlugssuaq will occur elsewhere on the ice sheet. Initial results for 2005 melt show that the melt continues to move further up the ice sheet reaching places where it has not been observed throughout the 27 year satellite melt record (Steffen and Huff 2005).

High Latitude Glaciers and Ice Caps

The world's glaciers and ice caps are estimated to contain the equivalent of 0.5 m of sea level, far less than the colossal Greenland and Antarctic ice sheets, and thus less of a threat in the long-term. However, because glaciers and ice caps are smaller and in many cases warmer than ice sheets, their responses to a changing climate may be more rapid. In that sense, their potential to impact sea level in the near term may be more significant than that of the large ice sheets.

Quantitative estimates of the mass change of these ice masses are limited, but there have been some elevation measurements that provide important information about their current state of balance in high latitudeds. In the late 1990s, airborne surveys were carried out on many of Alaska's glaciers, and these data were compared to ground surveys from the mid 1950s (Arendt et al. 2002). The results showed that in the four decades leading up 1995, the Glaciers lost the 57 km^3 of ice per year (or the equivalent of 0.14 mm of sea level each year), but between 1995 and 2000-2001, that rate of ice loss nearly doubled to 0.27 mm yr^{-1} of sea level, making Alaskan glaciers one of the most significant contributors to current sea level rise (Arendt, et al. 2002). In the summer of 2005, repeats of the original airborne surveys were conducted, which will provide important information as to whether the rate of ice loss has slowed, accelerated or remained the same.

Similar surveys of the Canadian ice caps indicate that they too have shrunk in volume such that their contribution to sea level was 0.064 mm yr^{-1} during the late 1990s. This is only one quarter that of Alaska, but like Alaska, the rate appears to have accelerated in the late 1990s (Abdalati et al. 2004). Like Greenland, the disappearing ice is generally coming from the low-lying regions that experience melt. The higher elevation accumulation zones show little or no change during the survey period. In Canada, however, the largest ice losses appear to be from the ice caps on Baffin Island, where the temperatures were not especially warm during the 1990s. Thus these changes are likely a continued response to the end of the Little Ice Age, which ended in during the 19^{th} century. Additional repeat surveys of some of these ice cap were also conducted in spring, 2005, with more planned for 2006. The 2000-2005 time period was significantly warmer around Baffin Bay than the 1995-2000 time period, so we expect ice losses to have increased in this area.

In the southern hemisphere, the major high-latitude ice cover (outside of Antarctica) is the Patagonian Ice Fields. Comparisons between surface field measurements and data from NASA's Shuttle Radar Topography Mission (SRTM) show that accelerating high-latitude ice loss is not only limited to the northern hemisphere. From 1968/75 (the periods of surface measurements) to 2000, the ice fields lost the sea level equivalent of 0.042 mm yr^{-1}, but from 1995-2000, that amount increased to 0.105 mm yr^{-1}. Their wastage is not of the same magnitude as the Alaskan glaciers, but relative to their size, they are shrinking much more rapidly (Rignot 2003).

Summary and Conclusion

Clearly the Earth's high-latitude glaciers, ice caps, and ice sheets are changing significantly. The satellite, aircraft, and in situ data from the last decade have revealed that the vast ice sheets respond very rapidly to changes in climate. These are evidenced by a) the acceleration and shrinking of glaciers that fed the collapsed Larsen B ice shelf, b) the rapid discharge and shrinkage of one of the fastest glaciers in the world, Greenland's Jakobshavn ice stream, and c) the seasonal acceleration in areas of melt on Greenland that can only be explained by the penetration of melt water. The associated sea level contributions are compounded by significant shrinking of Alaskan glaciers, Canadian ice caps, and the Patagonian ice fields, and these rates of change have accelerated in each case at the end of the last century.

At the same time, however, there has been growth in parts of the ice sheets, most notably East Antarctica, as a result of increased accumulation, and the slowing of ice some streams in West Antarctica. The question remains: which effects dominate on the ice sheets? In Greenland, the evidence suggests that the ice sheet is shrinking, but in

Antarctica, the total balance has not been determined, nor has its likely future behavior. We are confident of growth in East Antarctica's interior, but the balance at its climatically sensitive fringes, have not been fully assessed.

It is essential to recognize, that the processes that govern growth are generally slow: accumulation of relatively low-density snow in these vast polar deserts, where the annual snowfall is in many places less than a few tenths of a meter of water equivalent (much less in East Antarctica), and the slowing down of ice streams. The processes that cause the ice to shrink *can* happen much more rapidly, in particular accelerating flow rates and to a lesser extent surface melt with its positive albedo feedbacks. As a result, contributions of ice sheets to sea level rise are potentially more dramatic than their contributions to slowing or reversing that rise. In view of the societal vulnerability and the sensitivity of polar regions to polar changes, understanding how these high-latitude glaciers and ice sheets are changing is of critical importance.

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Table 1

Contributions of ice sheets and glaciers to sea level rise based on observations of the last decade (sources of numbers are provided in the text). Where estimates exist for more than one time period, the earlier is shown on the left and the most recent is on the right.

Ice Covered Region	**Sea Level Input (mm yr^{-1})**	
Greenland	+0.15 (1993/4-1998/9)	+0.20 (1997-2003)
Alaskan Glaciers	+0.14 (mid 50s - mid 90s)	+0.27 (1995-2000)
Canadian Ice Caps	+0.065 (1995-2000)	
East Antarctica*	-0.12 (1992-2003)	
Ross Ice Shelf Ice Streams	-0.07 (1997)	
Amundsen Embayment	+0.13 (1991-2003)	+0.24 (2002-2003)
Patagonian Ice Fields	+0.042 (1968/75 - 2000)	+0.105 (1995-2000)
Total of most recent values	+0.69	

*Does not include ice near grounding lines

Figure 1: Schematic diagram of an ice sheet with its individual mass balance components.

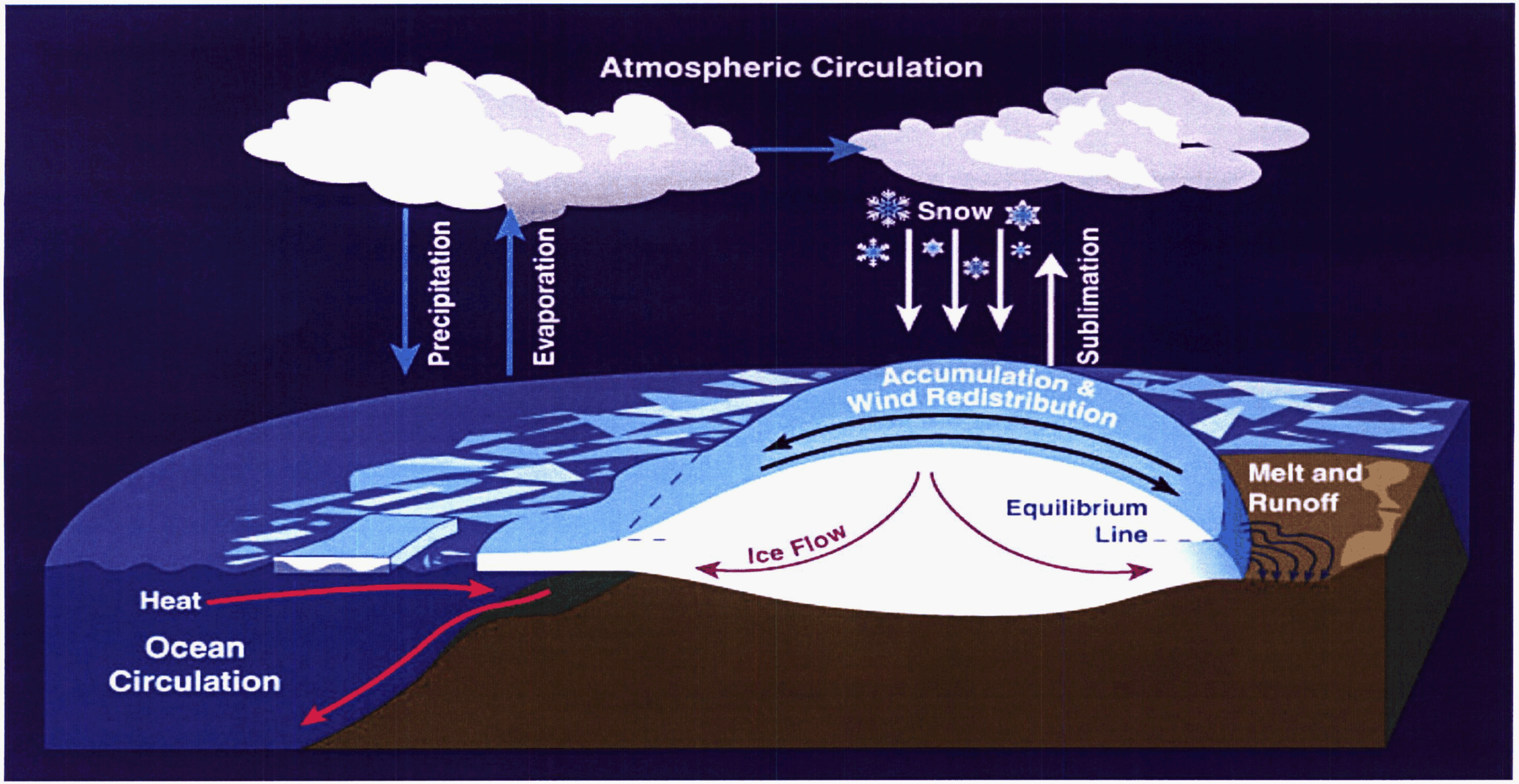
Figure 2: RADARSAT mosaic of Antarctica (© Canadian Space Agency).

Figure 3: Images of the Larson B ice shelf prior to and after its collapse in 2002. Images are from the MODIS instrument on NASA's Aqua satellite.

Figure 4: Average summer (June, July, and August) melt extent on the Greenland ice sheet (left), and maximum spatial extent of satellite derived melt during 2005. Pixels shown in red are pixels that did not exhibit melt during the 1979-2004 satellite melt record (Steffen and Huff 2005). Also identified in the figure is the Jakobshavn Isbrae area shown in more detail in Fig. 5.

Figure 5: Running surface melt water as it enters a moulin (left), and schematic of pathways that transport water from the surface to the bed (right). Both Figures are © AAAS (reprinteded with permission).

Figure 6: Landsat image of the Jakobshavn Isbrae and Fjord showing calving front locations from 1850. Locations from 1953 and earlier were adapted from Weidick (1995). Others were derived from satellite imagery.



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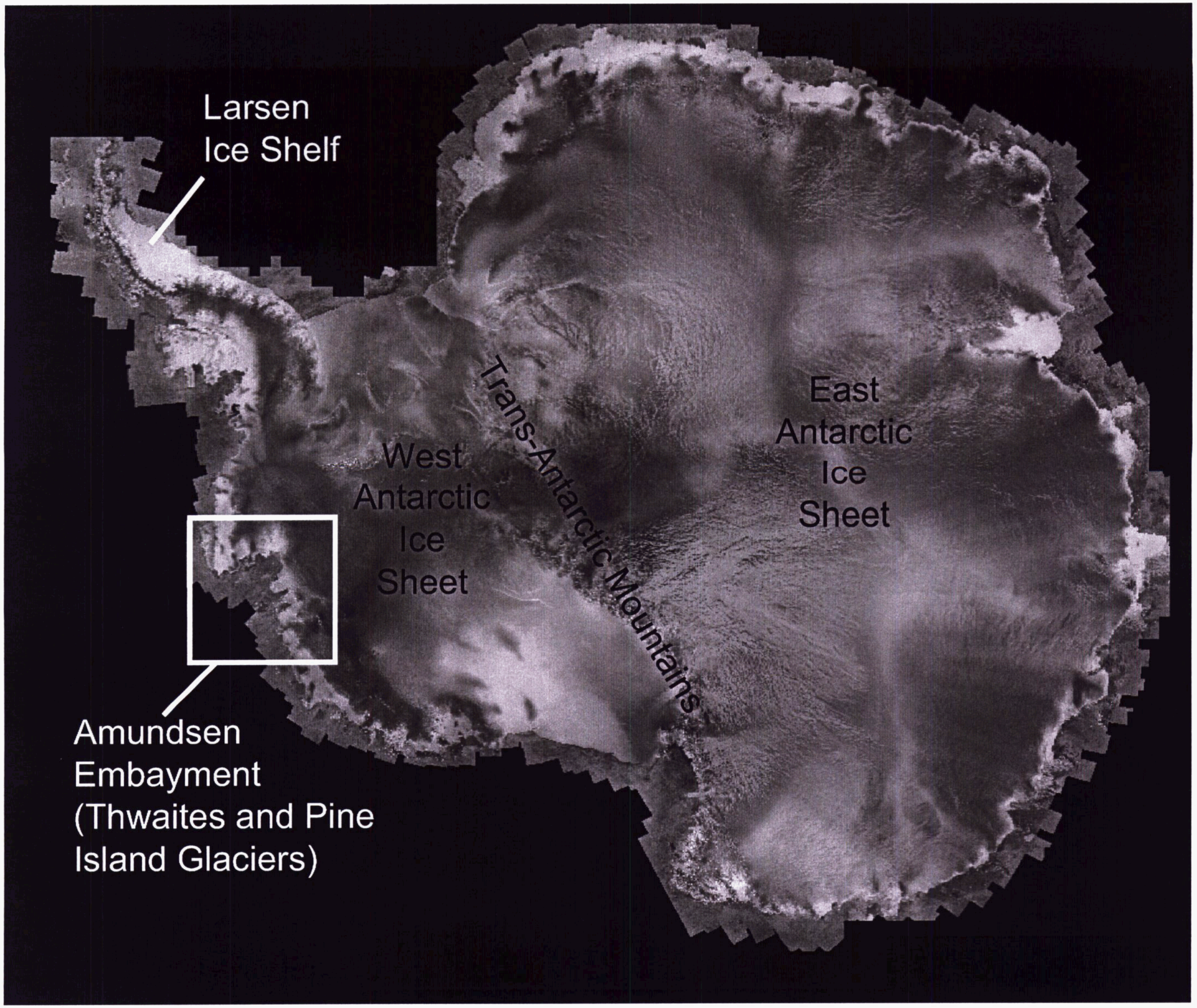

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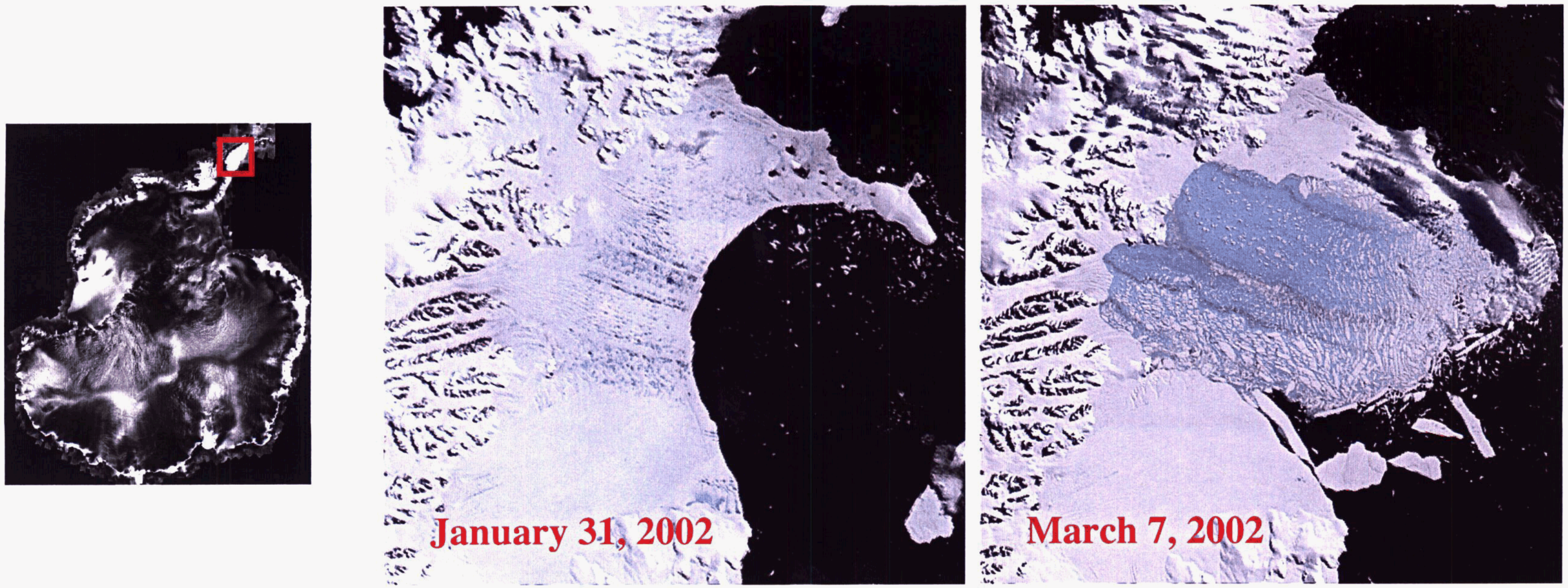

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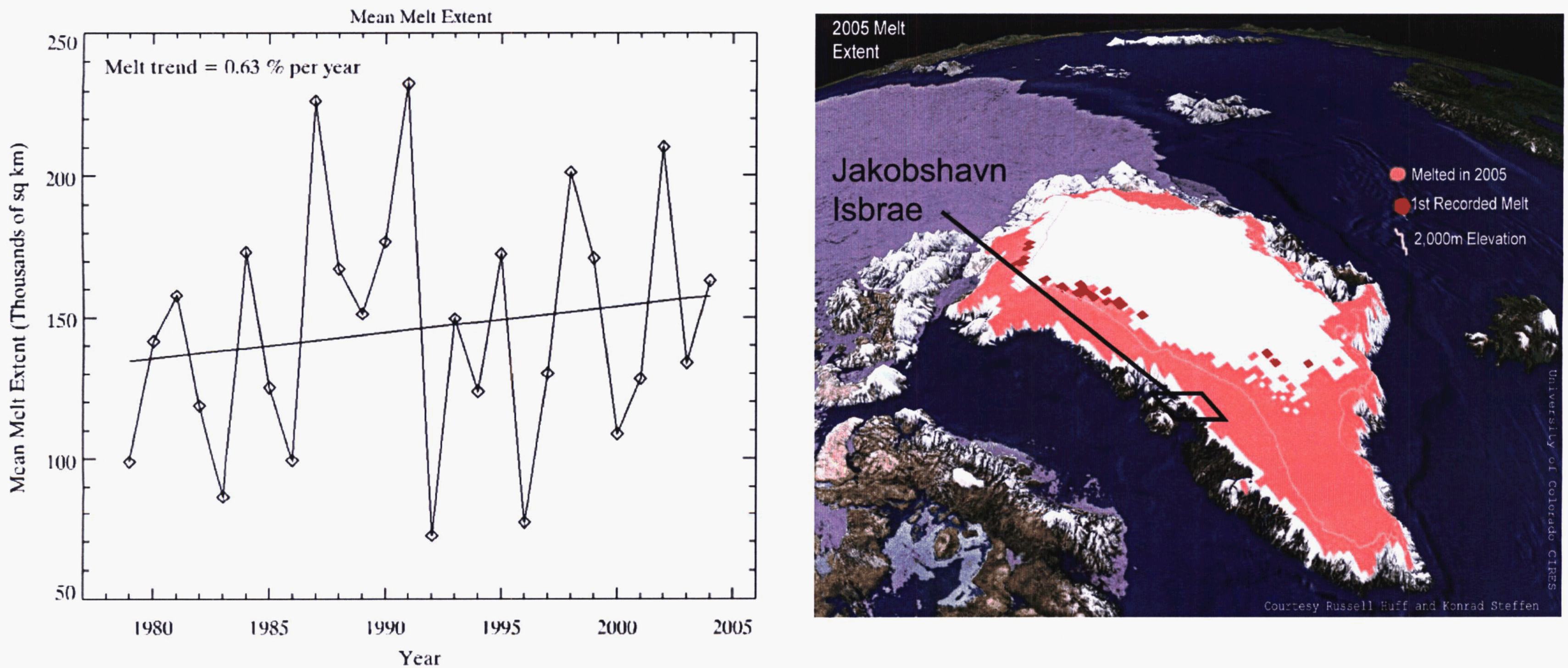

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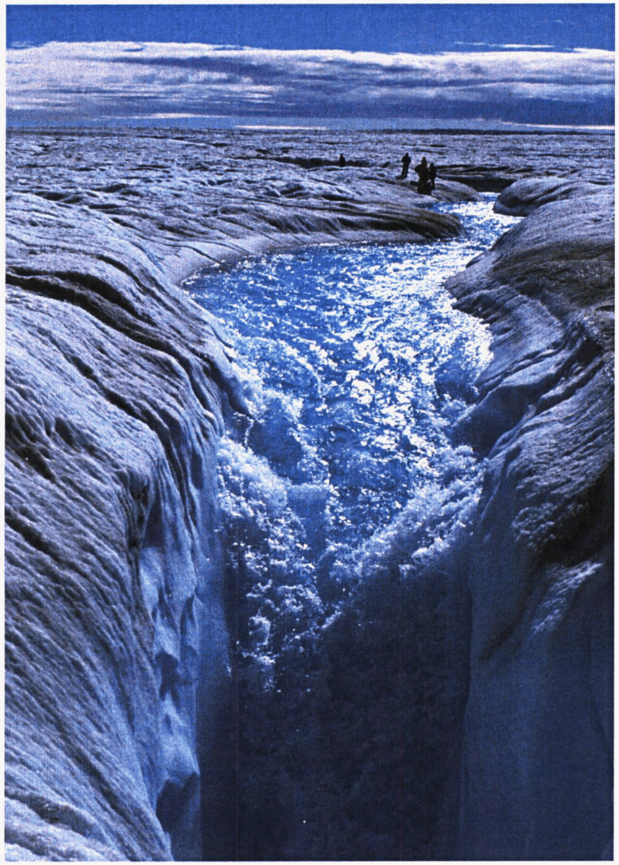

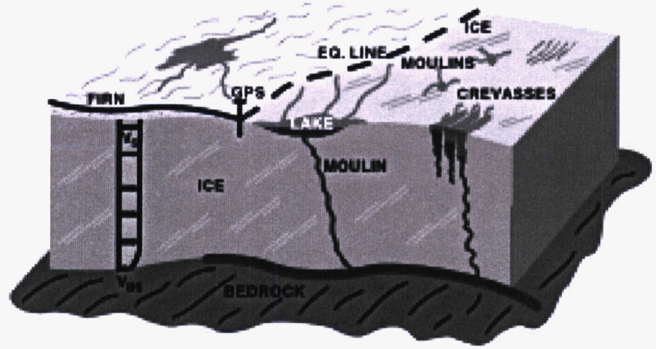

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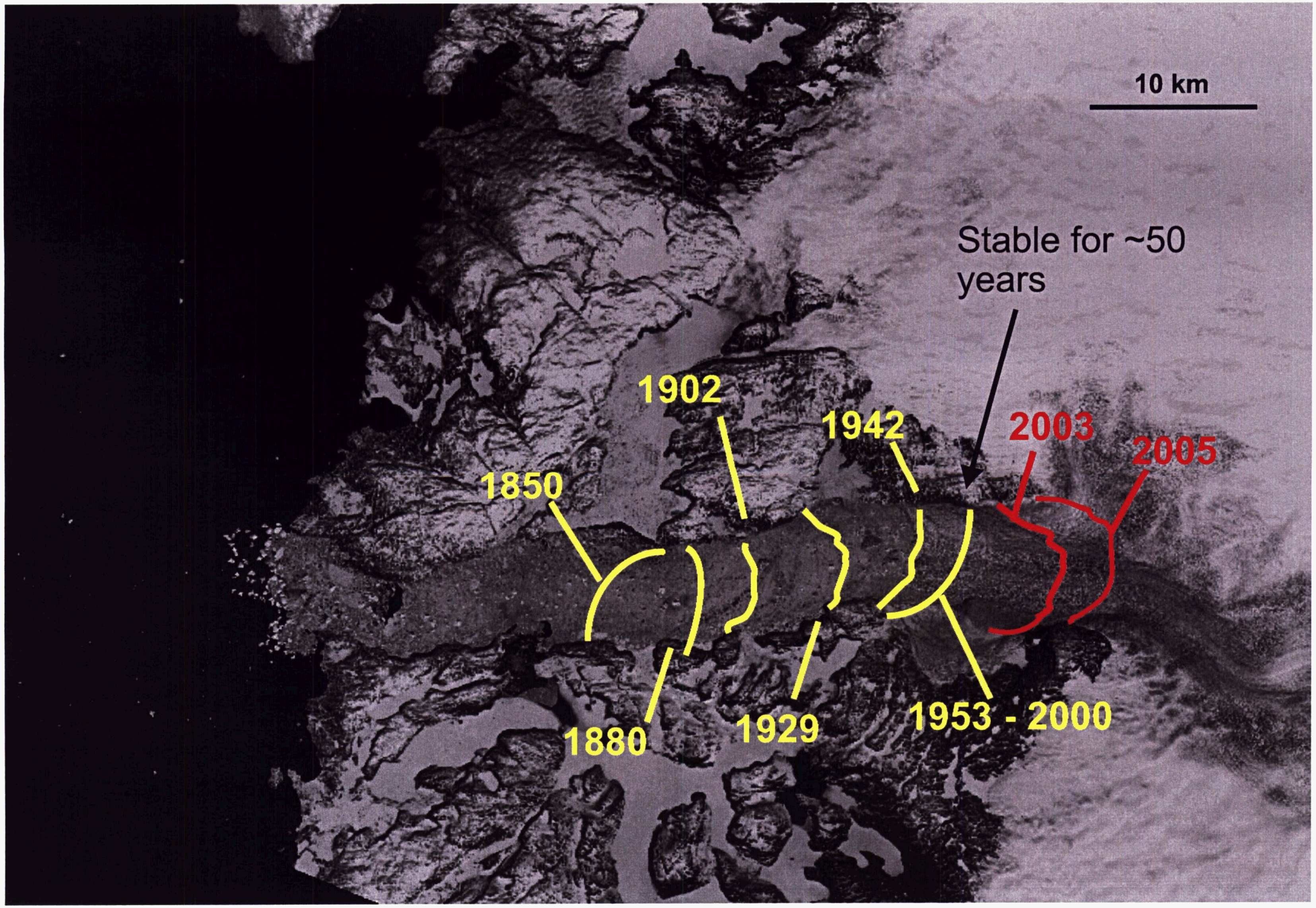

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