
(A) The Antarctic Ice Sheet and its Role in the Global System

(A.1) Main Geographic and Glaciologic Provinces of Antarctica

The most conspicuous property of Antarctica is its ice mass — most of the Antarctic continent's land-mass is covered by ice — ice sheets, glaciers, ice streams and ice shelves. All these features consist of ice and may thus be summarized as “glaciers”, but have different properties. An ice sheet covers large land areas and is flat and wide, the ice in the ice sheet flows at a low velocity, following gravitational forces, generally towards the ice sheet's margin. An ice stream is an area of ice flowing at a higher velocity than the surrounding inland ice, large ice streams drain the inland into the Circum-Antarctic ocean. The lower part of an ice stream draining into the ocean becomes afloat (at the line termed the grounding line), it forms a floating tongue. Many Antarctic ice streams and glaciers end in ice shelves, areas of ocean water covered by thick ice (more glaciologic terms are explained in the glaciologic glossary, section (I.1)). Often several glaciers and ice streams end in the same ice shelf, but there are also coastal areas of Antarctica that are not bordered by ice shelves. For instance, the Atlantic Ocean sector is fringed by ice shelves, with large ice streams flowing into those, including Slessor Glacier, Jutulstraumen, Stancomb-Wills Glacier and Recovery Glacier. Examples of coastline without ice shelves are Mawson Coast (W of Lambert Glacier), Knox Coast and Sabrina Coast in Wilkes Land.

Antarctica is commonly “divided” into East Antarctica and West Antarctica (see Figure A.1-1). While the divider between these two distinctly different parts of Antarctica is well-defined as the Transantarctic Mountains, running from east of the Weddell Sea across the continent to the west

of the Ross Ice Shelf, the terminology constitutes a misnomer, as the center is to the south — hence some parts of “East Antarctica” are west, some are east of the Transantarctic Mountains. It is generally accepted that “East Antarctica” is that part including Queen Maud Land, Enderby Land, MacRobertson Land, American Highland and Wilkes Land. (In maps plotted with the Antarctic Peninsula pointing to the top of the map, East Antarctica is to the right of the Transantarctic Mountains, West Antarctica is to their left.) East Antarctica contains the geographic South Pole. The coast of East Antarctica borders the eastern part of the South Atlantic sector, the Indian Ocean sector, and the western part of the South Pacific Ocean sector of the Circum-Antarctic Ocean. The geologic shield of East Antarctica is covered by the Earth's largest ice sheet, the East Antarctic Ice Sheet. As we shall see in the map part of the Atlas, East Antarctica has a fairly simple geography, except for the marginal (coastal) areas, with huge basins and separated by broad ridges.

Correspondingly, the continent-scale flow systems are simple. The only large ice stream-ice shelf system in East Antarctica is the Lambert Glacier/Amery Ice Shelf system, this is also the most northerly of the large Antarctic ice-stream/ice-shelf systems (except for ice shelves on the Peninsula). Queen Maud Land is the large part of Antarctica between the Weddell Sea and Lambert Glacier/Amery Ice Shelf, closer to Amery Ice Shelf is Enderby Land. MacRobertson Land and American Highland are smaller areas bordering Amery Ice Shelf (on the W and E, respectively). To the east is Wilkes Land, the largest and least

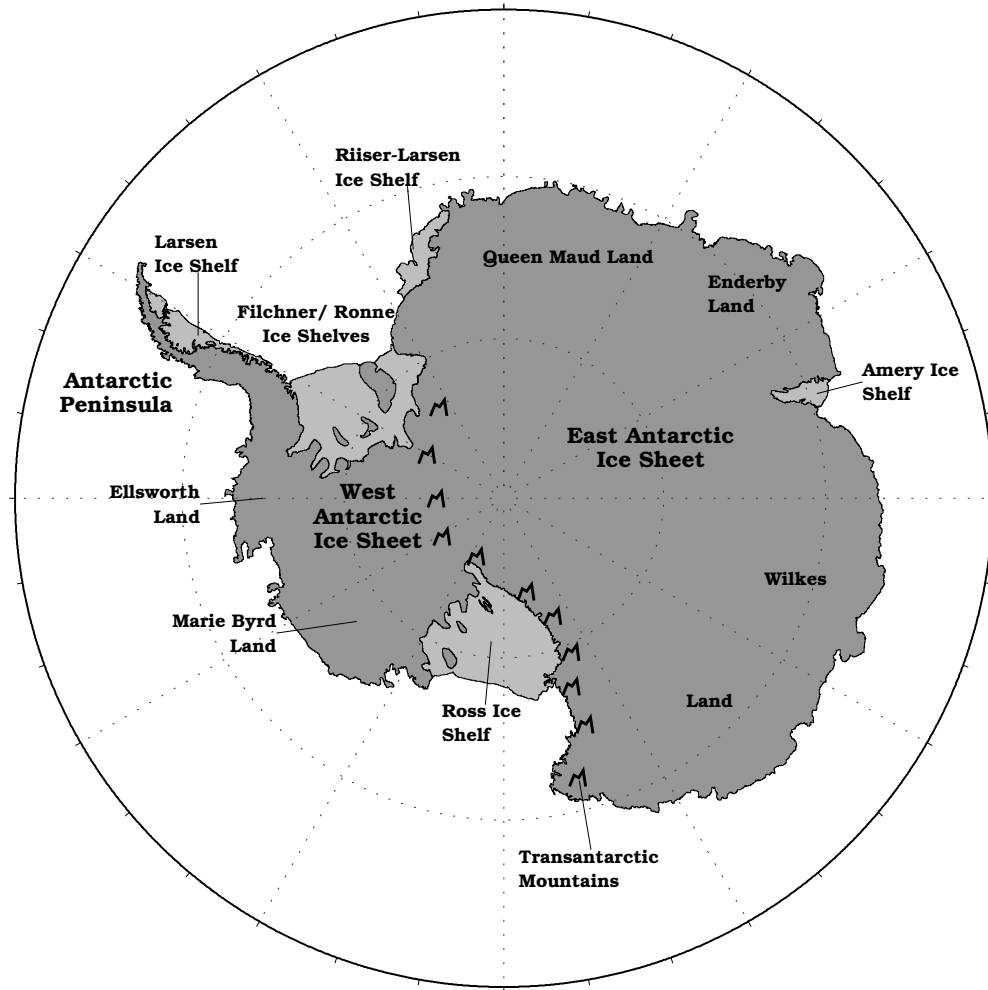


Figure A.1-1. Antarctica — Overview map.

explored part of Antarctica, extending from Lambert Glacier/Amery Ice Shelf to the Ross Sea sector and the Ross Ice Shelf. Surface gradients in East Antarctica are generally very low. Ice drains generally towards the ice sheet margin, and for 10% of the area to the Lambert Glacier/Amery Ice Shelf system. Three subglacial domes influence the flow direction over hundreds and thousands of kilometers: Valkyrie Dome near ($40^{\circ}\text{E}/77^{\circ}\text{S}$) in Southern Queen Maud Land, Dome Argus ($78^{\circ}\text{E}/81^{\circ}\text{S}$), and south of American Highland Dome Charlie ($125^{\circ}\text{E}/75^{\circ}\text{S}$) in Southern Wilkes Land. The Transantarctic Mountains include the Shack-

leton Range, the Pensacola Mountains (east of the Filchner Ice Shelf), continue in subglacial mountains, Queen Maud Land Mountains (bounding the southern Ross Ice Shelf), Queen Elizabeth Range, Churchill Mountains, Prince Albert Mountains and many other smaller ranges bordering the Ross Sea.

West Antarctica is geographically much more divided and smaller chambered than East Antarctica. Two large ice shelves, the Filchner-Ronne Ice Shelf (separated by Berkner Island but connected south of that island) and the Ross Ice Shelf. The

Filchner-Ronne Ice Shelf extends to 82.5° South (where Support Force Glacier enters) and to 83° South (where Foundation Ice Stream enters). The Ellsworth Mountains border Ronne Ice Shelf in the west and contain Antarctica's highest mountain, Vinson Massif (5140 m).

From west of the Ross Ice Shelf, the Antarctic Peninsula extends north to 63° S, with Clarence Island and Elephant Island near 61° S and the King George Islands at 62° S across the Bransfield Strait. The islands are considered part of Antarctica (and their presence contributes to the prestigious question of who first set foot on Antarctica, or sighted Antarctica). Contenders for having first set foot on the mainland include Nathaniel Palmer, an American whaler, Thaddeus Bellinghausen, captain for Russia, and Norwegian biologist Carsten Borchgrevink, who participated in H.J. Bull's expedition to Borchgrevink Coast, Vic-

toria Land, in 1894-95 and led the British Antarctic expedition in 1898-1890.

The Peninsula has a mountainous spine and a small-chambered topography with many mountain ranges, local glaciers, ice shelves and islands, the largest of which is Alexander Island. The northern part is Graham Land, the southern part Palmer Land.

The Ross Ice Shelf extends to 85.5° S, it is bordered by the Transantarctic Mountains on the west, with many ice streams draining from the interior of Wilkes Land and the Polar Plateau. In contrast, the east coast (Siple Coast) is characterized by a much less relief-energetic landscape of large ice streams that drain from Marie Byrd Land. A large volcanic province extends from the Jones Mountains at 94° W to the Fosdick Mountains at 145° W in Marie Byrd land. The coast of Marie Byrd Land and Enderby Land contains many ice shelves.

(A.2) Climate Change, Sea-Level Rise, and Changes in the Cryosphere

The Antarctic Ice Sheet plays a major role in the Global System. Under warming climatic conditions, as have been observed in the past to present decades, the Antarctic ice is reacting sensitively.

As a result of warming, one would expect an ice sheet to lose mass and a glaciers to retreat. Indeed, some glaciers in Antarctica have been retreating, an example is Pine Island Glacier on Walgreen Coast, Ellsworth Land. Not all Antarctic ice streams are retreating — an advance of Lambert Glacier averaging 1 km/yr over 10 years has been observed (Herzfeld et al. 1994, 1997).

Increasing temperatures do not necessarily result in mass loss in the Antarctic. To the contrary, in a warming climate, precipitation in Antarctica may increase; precipitation at Antarctic latitudes means snowfall, which alters the low accumulation rate and adds mass.

The ice sheet mass balance is the difference between mass input and mass output (or mass loss). Mass input processes are snowfall, rainfall, and condensation. Mass loss from an ice sheet can occur through evaporation, sublimation, surface and bottom melting, water runoff and iceberg discharge. At present, the average accumulation rate

in Antarctica is only 162 mm/yr water equivalent, much lower than the average accumulation rate of Greenland, which is 273 mm/yr water equivalent. Antarctica is an arid continent, and most of the accumulation is by redeposition of drifting snow. The equilibrium line, the line between accumulation and ablation areas, is close to sea level, and the ablation area constitutes only 1% of the total area of Antarctica. In contrast, two thirds of the area of the Greenland Ice Sheet belong to the ablation area.

The mass balance of the Greenland and Antarctic Ice sheets is, however, only known with an accuracy of 25% (Warrick et al. 1996). Mass and energy exchange processes change on seasonal to interannual time scales, and the general patterns of these smaller time-scale changes vary under climatic change. The response of large glaciers to changes is on the order of 1000 to 10000 years.

In a warming climate, the sea level will increase due to several causes. First, melting of glacier ice and mass loss by calving increases sea level. Numbers and models vary widely. The total ice volume of Antarctica is $29.000.000 \text{ km}^3$. It does not make much sense to convert all that to water equivalent

or ocean height equivalent, because it is unlikely that the entire Antarctic ice mass might melt, and other effects such as rebound of the continental plates would change the world's coasts, as a result of the redistribution of loads. Currently, the sea level rises about 2 mm/yr , half of that has been attributed to the melting of small glaciers (i.e. glaciers excluding Greenland and Antarctica) by Meier (1984). It is not known whether the ice sheets in total are presently contributing to sea-level rise. Second, warming climate causes warming of the World's oceans, and hence expansion of the volume of seawater, incurring further sea-level rise. Oceanographic (acoustic) experiments have been conducted that resulted in observations of an expanding ocean due to warming.

Changes in the ice mass, however, do rarely take place as a uniform surface lowering, but (1) thinning of the ice occurs predominantly in coastal areas (as established by Krabill et al. (1999) and Steffen and Box (2001) for Greenland), and (2) fast-moving ice streams and outlet glaciers and ice shelves react most rapidly to climatic changes. Consequently, the most important part of the Antarctic to investigate when looking for changes are the marginal areas of the Antarctic ice sheets. Mass flux occurs across the ice-ocean boundary. Ice is transported seaward by ice streams and outlet glaciers, ending in ice shelves or directly in the Circum-Antarctic Ocean, and iceberg calving occurs.

Two methodological aspects of the Atlas project facilitate investigation of the Antarctic margin: (1) Mapping of regional areas as part of the Atlas Scheme, and (2) exploitation of the neighbourhood structure through the geostatistical concept of the regionalized variable (these concepts will be explained in chapter C).

Ten percent of the entire area of Antarctica that is covered by ice is constituted by ice shelves. In recent years, the ice shelves in the northern latitudes, i.e. on the Antarctic Peninsula, have been disintegrating rapidly, as a consequence of climatic warming: One of the first such occurrences was the break-up of Wordie Ice Shelf (1984) (Vaughan 1993), followed by the break-up of Wilkins Ice Shelf (west of Alexander Island), parts of George VI Ice Shelf west of Palmer Land (between Palmer Land and Alexander Island), and most recently, Larsen Ice Shelf (2002) east of the Antarctic Peninsula (MacAyeal et al. 2002, Rott et al. 2002).

Müller Ice Shelf, a small ice shelf at ($67^{\circ}15'\text{ S}/66^{\circ}52'\text{ W}$) in Lallemand Fjord, Marguerite Bay, existed for a long time as the northernmost ice shelf on the western side of the Antarctic Peninsula, because it was protected by land around Lallemand Fjord, until it broke up. However, Wordie Ice Shelf, located farther south at 69° S , broke up earlier. Generally, ice shelves sheltered by bays and promontories are less susceptible to break-up than less protected ice shelves. Mechanisms for break-up are unknown and presently an object of scientific research, while the occurrence of meltwater on the surface of an ice shelf is clearly an indicator for warming and thus for possibly impending disintegration. Amery Ice Shelf is presently showing signs that a large iceberg will break off in the next years; however, that does not necessarily indicate break-up, as calving of icebergs, including huge ones of several tens of kilometers in diameter, occurs with a catastrophic nature.

Changes in ice streams occur in both a climatic and a dynamic context: Whereas the existence of climatic change is widely known and its influence discussed in public media as well as in the glaciologic community, the existence of dynamic properties of glaciers is much less known and hence a lesser objective of debate. All glaciers have their inherent dynamics and can, by virtue of their flow properties, be described as dynamical systems. Glaciers ending in fjords may have an internal dynamic cycle of advance and retreat on the order of 1000 years (a number that has been established for Alaskan fjord glaciers, Meier and Post 1969). A situation where one glacier is advancing while a neighboring glacier (in the same climate!) retreats, is not a rarity in Alaska, Greenland or Antarctica — this cannot be attributed to climatic effects. Reaction time of large Antarctic ice streams to climatic change is on the order of several thousand to tens of thousands of years, e.g. Lambert Glacier. An example of neighboring Antarctic glaciers that advance and retreat respectively are Mertz and Ninnis Glaciers in Wilkes Land.

The dynamical properties of glaciers deserve more attention. Under a condition of a warming climate, the fast-moving glaciers play a key role in any scenario of a break-up of the ice sheet.

An interesting dynamic phenomenon is that of glacier surges: During a surge, a glacier accelerates to many times (up to 100 times) its normal velocity, its surface breaking up into character-

istic crevasses. After the surge, which may last one to several seasons, the glacier returns to its usual speed. Some glaciers are surge-type glaciers, while others do not surge. Surges occur quasi-periodically. Some side glaciers of Lambert Glacier surge (most likely). Many unanswered questions are associated with glacier surges — the surge mechanism is unknown, why some glaciers surge and others do not surge, and why surge glaciers are limited to a subset of the earth’s mountain ranges (see Meier and Post 1969, Raymond 1987, Kamb 1987, Herzfeld 1998, Herzfeld and Mayer 1997).

Types of fast-moving ice include (Clarke 1987) continuously fast-moving glaciers, surge-type glaciers, tidewater glaciers, and the West Antarctic ice streams, which form their own class, moving absolutely rather slowly but otherwise sharing properties of fast-moving ice. Fast-moving glaciers are relatively rare but important.

(A.3) Modeling Versus Measuring

Studies of the effects of global warming on the cryosphere usually involve a modeling approach to processes in the global system. Any model is based on a physical model, commonly a dynamical system. Most models also contain observations on some variables. To simulate a scenario of change in the modeled system, the model is run, typically by keeping certain variables fixed while changing others (for instance, increasing temperature by 1 K), or by letting the model step through time. In both cases, the behaviour of the model and the outcome are noted and reported. As an example, in model runs the West Antarctic Ice Sheet is more susceptible to disintegration than the East Antarctic Ice Sheet. Difficulties exist in modeling more than one Earth system, for instance, in combining ice and ocean models, or only ice sheet models and ice shelf models (Ralf Greve, pers. comm., Huybrechts 1993).

Model results may be compared to observations for validation of the model, and, ultimately, understanding of the Earth system. The opposite approach to learning about the Earth starts from conduction of experiments, observations and measurements on the Earth’s surface, from the air and, in the last decades, from satellites. Technical ad-

Climatic changes have been occurring for millions of years, they are part of the astrophysical cyclicity of the Earth in the solar system, as discovered by Milankovitch (Milankovitch cycles of c. 20 kyr, 40 kyr, 100 kyr and 400 kyr). These cause ice ages and warm ages. The last ice age ended $\approx$ 8000 years ago. On the other hand, anthropogenically induced changes contribute to global warming — increased CO₂ emission, destruction of the ozone layer, and other forms of pollution — it is this contribution to global change that is the reason for policy discussions, and the reason to make us think about effects of human behavior on the environment. The relative magnitude of human-induced changes is a matter of heated debate, and the answer to this problem depends on the assessment of “natural” changes. The latter may in part be inferred from the geologic record (e.g., marine sediment cores and stratigraphic studies of marine environments from previous geologic times).

vance has brought new observational methods in all those fields, most dramatically in satellite remote sensing. New observational methods require new data analysis methods to utilize collected data and learn about processes on the Earth from those observations. The construction of the Antarctic Atlas from satellite radar altimeter data is part of the Earth-observation-and-data-analysis approach to Earth Sciences.

Collaboration between the modeling and the measuring/data analysis parts of the science communities is one of the most important tasks in the geosciences today. Calling for collaboration may sound trivial, but oftentimes real-world properties may not be formulated easily as model constraints; or model results may contradict glaciologic or geologic observations. The modeling community often holds that a model needs to be consistent in itself, or that adding another condition would make the model unnecessarily complicated and solution computationally prohibitive. Better models, and hence better understanding of our world, can only be achieved by taking better data into account; hence more and better observations along with improved mathematical data analysis methods are a prerequisite for learning about our planet.

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