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Coastal and Regional Currents of Antarctica

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The coastal current system around Antarctica is controlled by the interaction of several factors: the Antarctic Circumpolar Current in deep water to the north, the bottom topography of the coastal region, and the influence of the atmosphere – the local winds, and the massive seasonal variation in surface heat flux. These factors are first briefly described, and it is then shown how they affect the observed pattern of coastal currents. Antarctica has a long coastline, and the observations of its coastal and regional currents are sparse, mostly confined to summer except for a few long-term moorings, and concentrated in particular areas such as the Ross and Weddell Seas. This article attempts to provide an overall picture, but many regional anomalies, known and unknown, are omitted.

Like most other coastlines, Antarctica has a continental shelf and continental slope bordering the deep Southern Ocean. Here, however, the continental shelf is much deeper (400-600 m) than continental shelves in most other oceans (< 100 m), and in many places it is deeper closer to shore, with a sill of about 450 m depth at its outer edge (the shelf break). This unusual depth is attributed to the weight of ice on the continent, depressing the ground beneath. Further offshore the continental slope to the deep ocean is steepest in the upper 2 km with typical slopes of 3-6º, similar to those seen around other continents. There is much small-scale variation on this general topographic pattern: the shelf contains shallow plateaus and deep holes, and more particularly, submarine canyons are remarkably frequent, almost to the point of ubiquity in some sectors. These can help to drain dense fluid from the depressions on the shelf out to the deep sea.

North of the continental slope, though it is a notoriously stormy environment the average wind and its stress on the ocean are predominantly toward the east. This implies that the transport in the surface Ekman layer **[see article ??]** is predominantly toward the north. To conserve mass, the column of ocean water below the Ekman layer moves south, slowly and steadily driving deep water up the continental slope. This water, known as Circumpolar Deep Water (CDW), has been in the deep ocean for a long time (~ 1000 years), and is relatively salty, warm, low in oxygen and rich in nutrients when compared with the Antarctic coastal environment.

The coastal wind system is quite different from that over the deep ocean. The persistent clear sky over the continental land mass implies that the local atmosphere continuously loses heat by radiation, causing it to steadily subside to ground level. This cold air drains off the elevated continent in all directions in a boundary layer ~ 200 m thick, in a flow known as the katabatic wind. As this cold flow approaches the coast, the topographic gradient steepens and the wind speed increases, and the airflow is channelled preferentially into valleys where speeds of over 200 m/sec are not uncommon – the strongest winds on earth. This process continues throughout the year, but is strongest in winter. On reaching the level surface over the ice or water this cold dense airstream thickens and decreases in speed, often through the mechanism of a hydraulic jump. Where topographic channelling is not important, northward moving air is directed toward the west by the Coriolis force, and in consequence, at low levels over the continental shelf region the winds are generally toward the west.

At upper levels in the troposphere, however, the wind is predominantly toward the east, circling the Antarctic continent. The two main embayments, the Weddell and Ross Seas, are sheltered from this westerly wind stream by the mountains of the Antarctic Peninsula in the first case, and the mountains of Victoria Land in the second. These barriers direct the main topographic air stream around them to the north, where each flow separates from the barrier leaving a large recirculating clockwise eddy in the lee. The wind stress associated with each of these eddies then drives a corresponding clockwise recirculating oceanic gyre in each of the Weddell and Ross Sea basins. These gyres dominate the mean circulation in each basin and have diameters of order 2000 km, though the Weddell gyre is elongated towards the north-east, extending as far as 30ºE. Surface current speeds in these gyres are of order 0.08 m/sec. At deeper levels in the Weddell Sea two smaller gyres are evident, one on each side of 15ºW. There is also some evidence that the circulation in the Ross Sea below the mixed layer is also made up of three smaller gyres. A wind-generated gyre is also expected in the Prydz Bay region, but it is weaker and on a smaller scale than those in the Weddell and Ross Seas.

The cold air draining off the continent is considerably colder than the surrounding ocean, particularly in winter. In consequence, the ocean loses heat to the atmosphere and freezes to form pack ice. This causes an enormous seasonal variation in the extent of pack ice **[see article "Ice-atmosphere interaction"],** which retreats to somewhere near the edge of the continental shelf in summer, reaching a minimum in February. It then extends rapidly northward in Autumn and Winter due to the decreasing temperature, particularly in the Weddell Sea sector, reaching a maximum extent and thickness in late August. The associated surface cooling causes the water over the shelf to be well-mixed, and is termed Antarctic Surface Water (AASW). Near the coast, in regions where the katabatic winds are strong, open regions with little or no ice termed "polynyas" form, because the offshore winds are strong enough to blow the newly formed ice into deeper water faster than it forms. Such regions act as continuous sources of dense salty water because of brine rejection from the continuously forming sea ice. This environment is affected by Circumpolar Deep Water (CDW) moving onto the shelf from the deep ocean to the north: the CDW mixes with the AASW to form a new identifiable water mass, Modified Circumpolar Deep Water (MCDW), in most places except the Weddell and Ross Seas. These and other water masses are identifiable by temperature and salinity characteristics, but the overall density variations over the shelf remain weak.

In consequence, wind-driven currents over the shelf are expected to be largely barotropic (meaning that they do not vary much in the vertical), with simple structure, and not particularly strong. The prevailing easterly winds produce the observed westward "East Wind Drift", which is prevalent around most of the continent excepting the Ross and

Weddell Seas. The southward Ekman transport due to this wind tends to cause downwelling at the coast, which helps to keep the shelf water homogeneous. The East Wind Drift is weaker in winter because the thick ice cover resists wind-driven motion. Between the coastal easterly wind region with southward Ekman transport and the main ACC region to the north with northward Ekman transport lies a broad region of Ekman divergence, which is the main driver for the rising of the circumpolar deep water (CDW), up the slope and onto the shelf at most longitudes.

In most coastal environments around the world, the main currents are situated over the continental slope. However, there is no evidence of an extensive current over the Antarctic continental slope. A westward "Polar Slope Current" has been observed in the lower part of the water column north of the South Shetland Islands (near the tip of the Antarctic Pensinsula), but this has not been observed at other locations. The natural horizontal scale for deep water currents – the Rossby deformation radius $R_0 = NH/f$, where H is the vertical scale (≤ depth of ocean), N the buoyancy frequency of the density stratification and f is the magnitude of the Coriolis frequency, is only about 12 km in these polar latitudes because of the weak density stratification and large f. Hence there may be significant motion over the slope on these relatively small scales near the bottom or near the surface (including eddies) that has not yet been observed.

Tidal amplitudes (sea surface height variations) and currents are not large in Antarctic waters, but are sufficient to be important for mixing processes in certain areas, namely the Weddell and Ross Seas. The semi-diurnal M_2 and S_2 tides are small in the Ross Sea because of a nearby amphidromic point, but M_2 reaches amplitudes of up to a metre in the western Weddell Sea, giving tidal currents there of order 10 cm/sec. S_2 has approximately half that amplitude there, with a similar pattern. It is possible that these tides generate significant semidiurnal internal tides at the shelf break in the Weddell Sea, and contribute to mixing processes associated with Antarctic Bottom Water formation. Elsewhere around the coast, the semi-diurnal amplitudes are small. The leading components of the diurnal tide (K_1 and O_1) have amplitudes of about 0.3 metres around the entire coast, increasing to over 0.4 metres in the Weddell and Ross Seas. Internal waves of diurnal frequency are not possible poleward of 30º latitude, but there is evidence of diurnal tidally forced continental shelf waves near the shelf break in the Southern Weddell Sea, apparently generated by diurnal tidal currents interacting with local topographic features.

A different type of current is the circulation that is driven by melting underneath the ice shelves. At most longitudes around the continent, ice is slowly pushed off the land forming ice shelves hundreds of metres thick that float on the water, extending seaward from the grounding line for distances ranging from tens to hundreds of km, up to thousands of km in the Weddell and Ross Seas. Warm salty circumpolar deep water flows southward at depth and melts some of the underside of the ice sheet, producing cooler fresher water that is buoyant and rises up along the bottom of the sloping ice sheet in the form of a gravity current (i.e, driven by buoyancy). This drives a vertical circulation of inflowing warm salty water toward the ice sheet at depth, with a relatively fresh outflow from it in the upper 200 metres of the ocean. Some re-freezing of the melt water on the ice sheet may occur as it rises, forming marine ice, which is manifested later as green icebergs. Though the magnitude of the circulation may be measured in Sverdrups (10^6 m^3/sec), inflowing current speeds are very small, and are of order 10 cm/sec in the rising gravity current with thickness of several metres. The process works in the vertical, but there is a lot of horizontal motion in these circulations, depending on the subsurface shape of the ice sheet and other conditions.

Near the edge of the continental shelf, in a general sense the circumpolar deep water over the slope meets the waters of the shelf. The latter have been affected by surface cooling, and are generally denser than the CDW, and this density difference implies a westward geostrophic current along the shelf break. This semi-permanent feature is narrow, with a typical width of 50 km and current speeds of order 0.1-0.3 m/sec, and has no signal in the surface layer. It is known as the Antarctic Slope Front, and appears to be present at most longitudes, with the exception of the region westward of the Drake Passage to 130ºW (which includes the Amundsen and Bellingshausen Seas and the west of the Antarctic Peninsula). Along the shelf break across the Weddell and Ross Seas, this front develops a “V”-shaped profile, a feature that becomes progressively stronger from east to west across each Sea. In this flow, the isopycnals are depressed downwards over the shelf break, and the transport in the current is mainly in the relatively fresh water inside the V. Antarctic Bottom Water (potential temperature ~ -1º, salinity > 34.6 ppt) is produced by mixing of dense cold high salinity shelf waters with warmer fresher water near the shelf break at the base of the “V” of the Antarctic Slope Front. This mixing process produces water in substantial quantities that is denser than any water in the deep Southern Ocean to the north, and spills over the shelf break to descend down the continental slope. This process occurs in the Weddell and Ross Seas, in the Adelie depression at 145ºE, and possibly also to a lesser extent in Prydz Bay. In the Weddell and Ross Seas, this dense water is formed along the southern shelf edge during most of the year, and flows northwards along the western shelf and slope where its buoyancy causes it to slowly descend to the ocean floor. The water formed in the Adelie depression mainly leaks out through submarine canyons, which are relatively localised features that facilitate direct descent of dense water down the slope. In contrast, in the Weddell and Ross Seas the bottom water appears to descend as a broad continuous sheet, slowly moving north. These dynamics are controlled by a combination of buoyancy, bottom drag, bottom slope and flow rate, which determine the dense layer thickness relative to the bottom Ekman layer thickness, an important parameter for the dynamics. In these regions, however, the details of the bottom topography have not been well-observed, because of the continuous year-round cover by ice, and it is possible that canyons (or at least, variations in slope) may be significant here also. The detailed dynamics of bottom water formation and its connection with the structure of the Antarctic Slope Front are not yet resolved. Some of the features described are shown schematically in Figure 1.

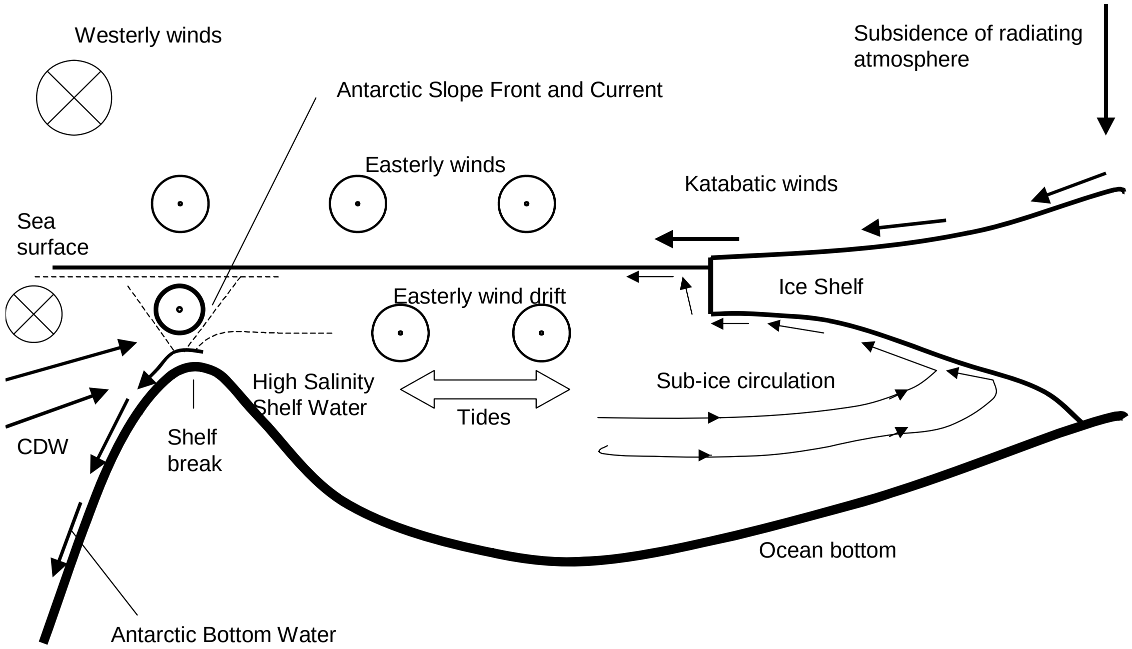

Figure 1 (Baines) Schematic of a north-south vertical section showing some of the aspects of Antarctic coastal currents described in the text. CDW is Circumpolar Deep Water, dashed lines denote isopycnals, arrow heads and tails denote wind and current direction.

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