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Inverted Circulations for the Southern Ocean

The Southern Ocean (Fig. 13.1) is bounded by the Antarctic continent to the south and the world ocean to the north; the Polar Front forms the boundary between the polar and subpolar water masses. The area of the Southern Ocean south of the Polar Front is about 3.8×10^7 km^2. The ocean floor around Antarctica has four basins (the Weddell–Enderby, South Indian, Southwest Pacific, and Southeast Pacific basins) with depths exceeding 4,500 m, separated by broad submarine ridges and plateaus. The continental shelves surrounding the Southern Ocean are generally quite narrow; the exceptions being the two broad (about 400 km) and deep (about 400 m) shelves of the Weddell and Ross seas. Shelf regions are further characterized by irregular depressions and submarine canyons and by glacial ice shelves which extend seaward from the continent. The Antarctic shelf and bottom waters are cold, dense water masses which have relatively high concentrations of the gases that the ocean acquires from the atmosphere, such as oxygen. They form close to the sea surface near Antarctica, then flow away from their source and sink, and then they introduce water with near-surface characteristics while moving into the deep ocean. This process, usually called ventilation, is associated with important fluxes of heat, salt, nutrients, and gases.

The absolute currents are inverted from the (T, S) fields from WOA using the P-vector method. The general circulation in the Antarctic is characterized by the Antarctic Circumpolar Current, Antarctic Coastal Current, and Antarctic gyres.

13.1 Antarctic Circumpolar and Coastal Currents

Vertically integrated annual mean velocity is calculated from the WOA (T, S) fields using the P-vector method (Fig. 13.2). The water flows around Antarctica in a clockwise direction (the Antarctic Circumpolar Current) with gyres and eddies.

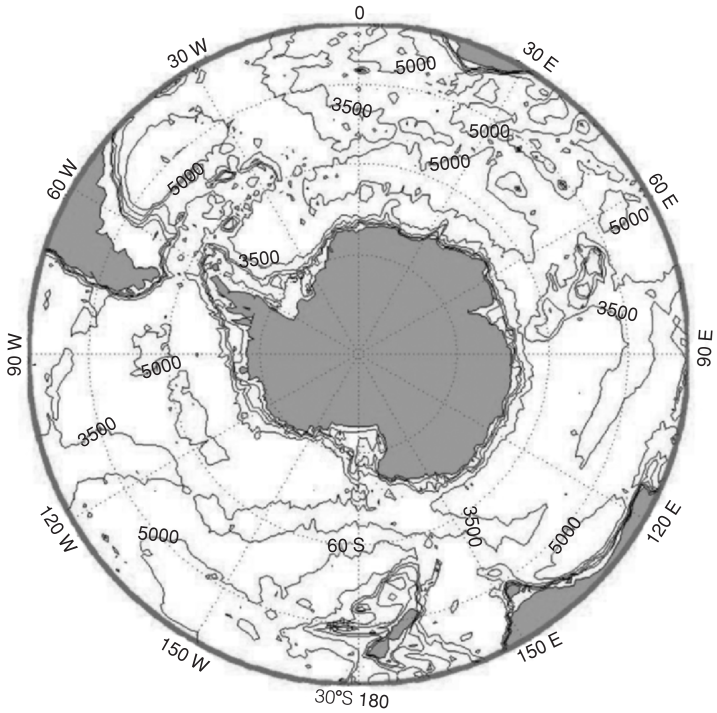

Fig. 13.1. Bathymetry of the Southern Ocean

The Antarctic Circumpolar Current is the most important current in the Southern Ocean, and the only current that flows completely around the globe. It encircles the Antarctic continent and flows eastward through the southern portions of the Atlantic, Indian, and Pacific Oceans. This current is arguably the "mightiest current in the oceans" (Pickard and Emery 1990). Despite its relatively slow eastward flow of less than $20\,\mathrm{cm\,s^{-1}}$ in regions between the fronts, it transports more water than any other current (Klinck and Nowland 2001). It extends from the sea surface to depths of 2,000–4,000 m and can be as wide as 2,000 km. This tremendous cross-sectional area allows for the current's large volume transport. The Antarctic Circumpolar Current's eastward flow is driven by strong westerly winds. The average wind speed between 40 and 60°S is $8-12\,\mathrm{m\,s^{-1}}$ with strongest winds typically between 45 and 55°S. Historically, the Antarctic Circumpolar Current has been referred to as the 'West Wind Drift' because the prevailing westerly wind and current are both eastward.

The Antarctic Circumpolar Current is an intense flow around the Earth without interruption and displays little attenuation with depth. It is strong over the northern slope of the midocean ridge in the southwest Pacific, in

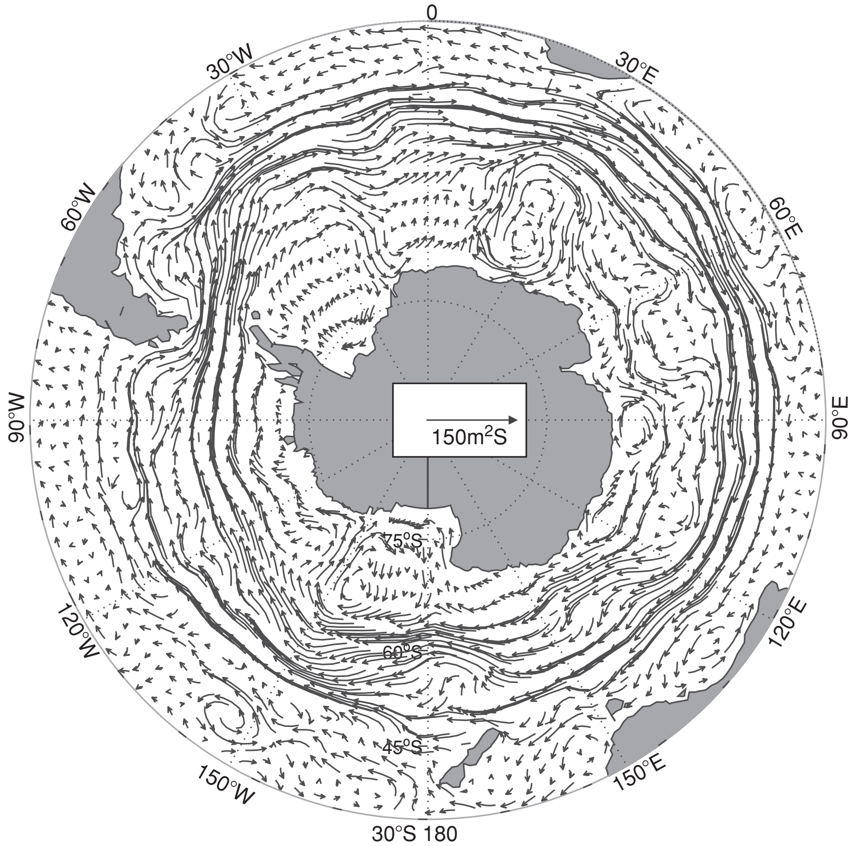

Fig. 13.2. Vertically integrated annual mean velocity is calculated from the WOA (T, S) fields using the P-vector method (from Chu and Fan 2006, Journal of Marine System)

Drake Passage, and the southwest Indian Ocean immediately below the Agulhas return current.

The computed monthly mean volume transport through the Drake Passage using the P-vector method is around 156 Sv with a small seasonal variation (Fig. 13.3), which compares well with recent year-long measurements of the transport of the Antarctic Circumpolar Current through Drake Passage (e.g., Nowlin et al. 1977; Bryden and Phillsbury 1977; Fandry and Pillsbury 1979; Whitworth 1983; Whitworth and Peterson 1985). These observations indicate the mean annual transport to be 134 Sv with an uncertainty of about l0%; the instantaneous flow may vary from the mean by as much as 20% (Nowlin and Klinck 1986).

In a major review of the structure and dynamics of the Antarctic Circumpolar Current, Nowlin and Klinck (1986) note that the Antarctic Circumpolar

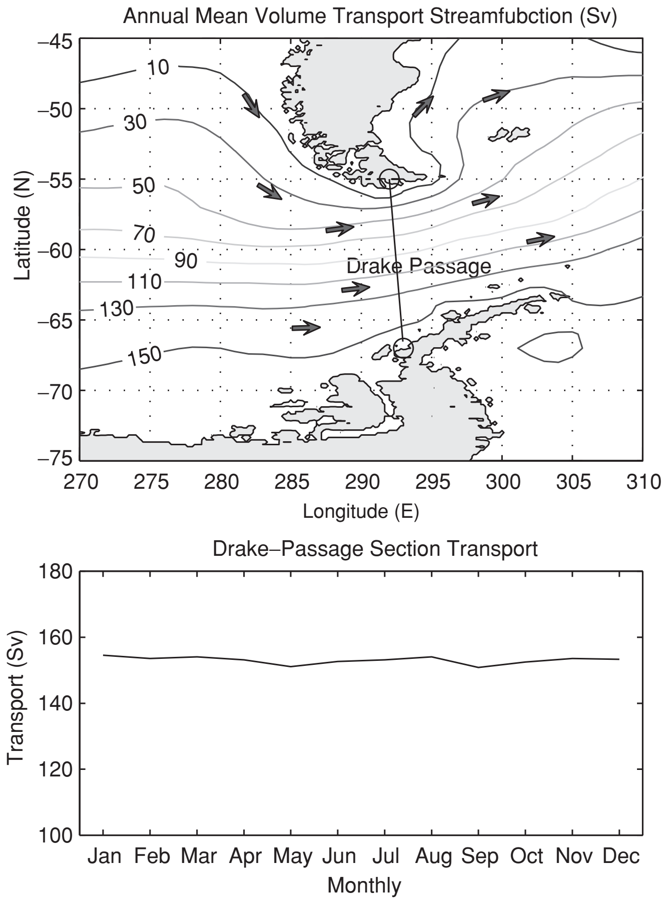

Fig. 13.3. The inverted (**a**) annual mean monthly volume transport stream function (unit: Sv) and (**b**) monthly mean volume transport through Drake Passage calculated from the WOA (T, S) fields using the P-vector method. Note that the seasonal variability is weak

Current exists as a banded structure, with multiple narrow jets associated with strong lateral density gradients at the sub-Antarctic and polar fronts. The position of these fronts is highly variable, and excursions of upto 100 km in l0 days have been observed. These meanders can lead to the formation of eddies and current rings (Joyce et al. 1981; Bryden 1983).

The Antarctic Coastal Current is the name commonly given to the narrow, westward-flowing current that tends to follow the continental margin (Sverdrup 1953). This flow lies south of the belt of low atmospheric pressure that extends around the continent at roughly 65°S. This current is not completely circumpolar, but instead becomes part of the clockwise gyres in the Weddell and Ross seas (see Fig. 13.2).

13.2 Cyclonic (Clockwise) Weddell Double Gyres

Figure 13.2 also shows the existence of several gyres in the western Weddell basin and north of the Ross Sea and south of the Antarctic Circumpolar Current. The horizontal structure and strength of the Weddell Gyre has been of interest to oceanographers for decades. Early estimates were based on (sparse) hydrographic data; which were used to conclude that there is a double-cell structure, at least in the baroclinic fields. However, this could not be confirmed by more recent measurements. Uncertainty also existed with respect to the magnitude of the mass transport in the Weddell Gyre, which was estimated to be between 30 and 70 Sv.

In the Weddell Sea, which probably contributes the most to the Bottom Water formation, the water flows westward under the influence of the Coriolis force as it sinks, forming a thin layer of extremely cold water above the continental slope. It mixes with the overlying water, which is recirculated with the large cyclonic eddy in the central Weddell Sea. The Weddell Sea is one of the few places in the world ocean where deep and bottom water masses are formed to participate in the global thermohaline circulation. The characteristics of exported water masses are the result of complex interactions among surface forcing, significantly modified by sea ice, ocean dynamics at the continental shelf break and slope (Foldvik et al. 1985; Muench and Gordon 1995), and subice shelf water mass transformation.

The inverted monthly (January, April, July, October) mean volume transport stream function Ψ and vertically integrated velocity (U, V) fields (Fig. 13.4) show a double-gyre structure of the Weddell Gyre as suggested by the hydrographic observations (Mosby 1934; Deacon 1979; Bagriantsev et al. 1989) and the numerical simulation of a regional coupled ice-ocean model (Beckmann et al. 1999). There is a western cell filling the western Weddell Basin, and another (even stronger) mostly confined to the deep basin northeast of Maud Rise. Both have a maxima that exceed 50 Sv in the annual mean.

Seasonal variability in (Ψ, U, V) is very weak. Maximum Ψ-value in the vicinity of the two cells is around 109 Sv. Minimum value of Ψ is around 55 Sv in the western Weddell Gyre and 39 Sv in the eastern Weddell Gyre. Thus, the volume transport is around 54 Sv associated with the western Weddell Gyre and 70 Sv associated with the eastern Weddell Gyre.

Quantitatively, the inverted transport compares well with calculations based upon observations along the Joinville Island-Kapp Norvegia section $(30 \pm 10\,\mathrm{Sv})$ as well as more recent measurements along the Greenwich meridian $(60 \pm 10\,\mathrm{Sv})$. The double cell structure persists throughout the year, but is most pronounced in austral winter. For example, this is consistent with earlier estimations such as 97 Sv by Carmack and Foster (1975) who utilized short-term current meter measurements and 76 Sv by Gordon et al. (1981) who computed the wind-driven transport of the Weddell Sea using Sverdrup dynamics, balanced by a western boundary current along the Antarctic Penin-

Fig. 13.4. Inverted monthly mean volume transport stream function and vertically integrated velocity vectors in the Weddell Sea (From Chu and Fan, 2006, Journal of Marine Systems)

sula. Deacon (1982) reviewed the physics of the Weddell Gyre in relation to ecological cycles and noted that southward flow along the eastern side of the Weddell Gyre appeared to be a critical factor determining krill cycles.

Figure 13.4 also shows the Weddell-Scotia Confluence in the northern end of the Weddell Gyre that lies to the northeastern side of the Antarctic Peninsula. It forms by the convergence of the Antarctic Circumpolar Current passing through Drake Passage and the recirculating flow of the Weddell Gyre (Gordon et al. 1977). This region is of considerable biological importance (Deacon and Foster 1977; Nelson et al. 1987). Foster and Middleton (1984) emphasized the eddy field lying downstream of the confluence.

13.3 Anticyclonic Ross Gyre

The inverted monthly (January, April, July, October) mean volume transport stream function Ψ and vertically integrated velocity (U, V) fields (Fig. 13.5) show a single gyre in the Ross Sea with the westward flow in the southern Ross Sea as pointed out by DeMaster et al. (1992) on the basis of moored current meter data. The anticyclonic (anticlockwise) Ross Gyre dominates the circulation in the Southeast Pacific Basin, between 160°E and 140°W.

The Ross Gyre extends from the surface to the deep ocean, and is approximately one-half to one-third as strong as the Weddell Gyre. Circumpolar Deep Water enters the Ross Gyre at its eastern end, and is ventilated by the shelf waters of the Ross Sea. Salinity and oxygen distributions show that the influence of shelf waters can be traced beyond the Ross Gyre into the mid-depth waters of the South Pacific Ocean.

Seasonal variability in (Ψ, U, V) is stronger in the Ross Sea (Fig. 13.5) than in the Weddell Sea (Fig. 13.4). The volume transport is around 80 Sv associated with the Ross Gyre. Such a strong cyclonic gyre represents important areas of biogenic production and potentially large sources of biogenic material to the water column and sediments. The inverted Ross Gyre is consistent with the current meter moorings (Pillsbury and Jacobs 1985), which show that the general circulation in the Ross Sea surface waters is cyclonic, with a slow southward flow in the central and eastern Ross Sea (the eastern part of the inverted Ross Gyre).

Questions and Exercises

(1) The Antarctic Circumpolar Current is the most important source of current in the Southern Ocean, and the only current that flows completely around the globe. Figure 13.2 shows the Antarctic Circumpolar Current meandering and eddy generation. Discuss the mechanisms causing the eddy formation.
(2) Discuss the effect of the Antarctic Circumpolar Current on the global climatic system.

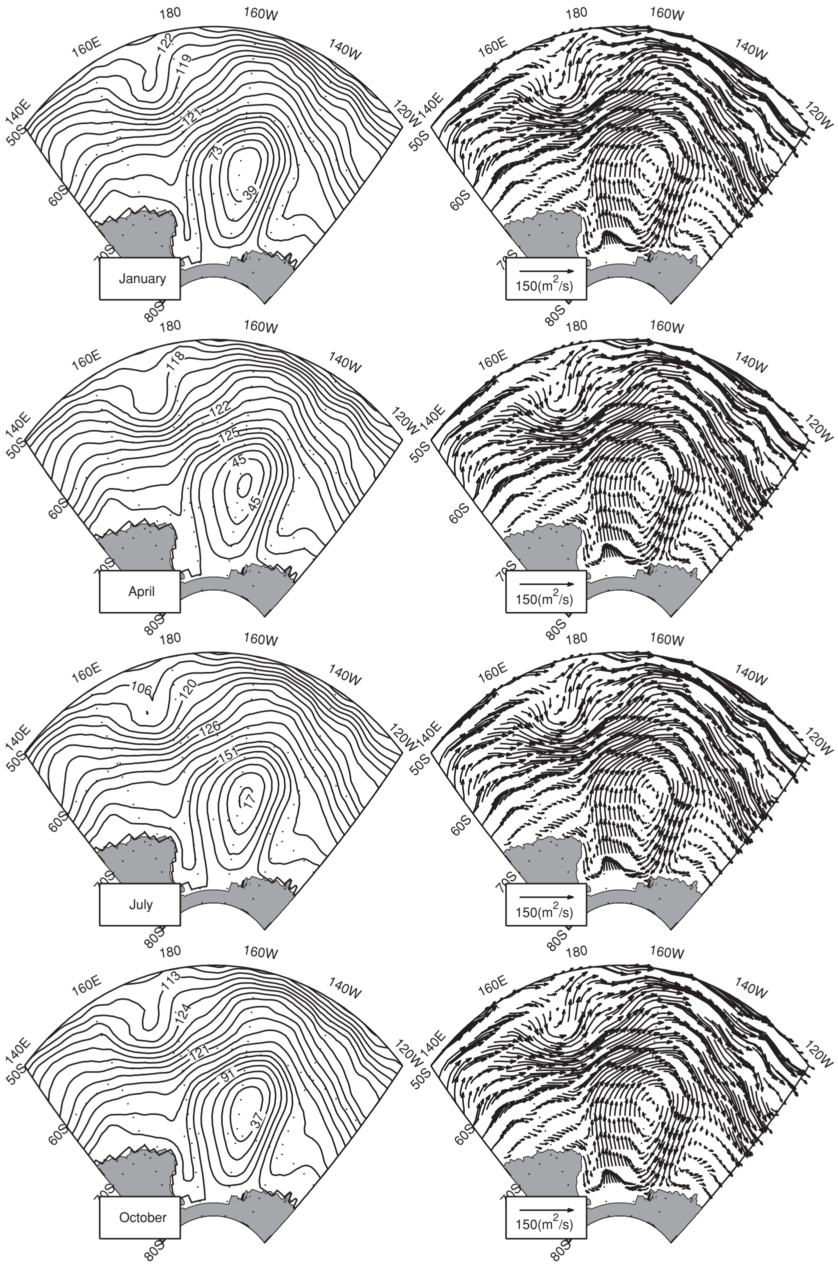

Fig. 13.5. Inverted monthly mean volume transport stream function and vertically integrated velocity vectors in the Ross Sea (From Chu and Fan, 2006, Journal of Marine Systems)

(3) The volume transport across the Drake Passage is estimated as 156 Sv from WOA (T, S) data using the P-vector method. Compare this value with the estimations by other authors after searching the reference.
(4) Figure 13.3 shows very weak seasonal variability. Is it realistic? What is the reason for that?
(5) Compare between the bathymetry of the Southern Ocean (Fig. 13.1) and the volume transport stream function in the Weddell Sea (Fig. 13.4). Can you speculate the topographic effect on the formation of the Weddell Double Gyres?
(6) What is the effect of the Weddell Double Gyres on the formation of the Weddell Polynya?
(7) What are the major features of the Ross Gyre?
(8) Find other gyres and their dynamic characteristics in the Southern Ocean using the inverted velocity data in the enclosed DVD-ROM.