12

Inverted Circulations in the Atlantic Basin

Setting aside the part of the Pacific, west of New Zealand and the Tonga–Kermadec Ridge, which has no counterpart in the Atlantic, there is some correspondence in the features. The general circulation of the Atlantic Basin is represented by vertically integrated velocity or volume transport stream function (barotropic) and three-dimensional absolute velocity (baroclinic). Figure 12.1 shows the volume transport stream function for the Atlantic Basin that is calculated by using the method depicted in Chap. 8. Comparing Figs. 12.1 to 11.1, we find that each basin (Atlantic and Pacific) has an anticyclonic subtropical gyre, which are the western and eastern boundary currents.

For the Atlantic Basin, there is some correspondence between the transports north and south of the equator along the side from the Caribbean and Gulf of Mexico, which has no counterpart in the South Atlantic. The midlatitude anticyclonic gyres in the North Atlantic and the South Atlantic have a comparable strength (50 Sv). We may also identify the following major features from Fig. 12.1: the Gulf Stream, the Labrador Basin cyclonic gyre, and the Brazil–Malvinas confluence zone.

12.1 North Atlantic Ocean Circulation

12.1.1 General Description

Physical oceanographers have been estimating the North Atlantic Ocean circulation for relatively long period. Most estimation was on the basis of geostrophic calculation and inverse (e.g., box, β-spiral, P-vector) methods using hydrographic data. Fuglister (1960, 1963) published the seminal collection of hydrographic data in the Atlantic for the early post-World War II era. Wright and Worthington (1970) and Worthington and Wright (1970) produced hydrographic and water mass atlases. The atlases by Fuglister, Worthington, and Wright are useful. Dietrich's (1969) atlas of the northern North

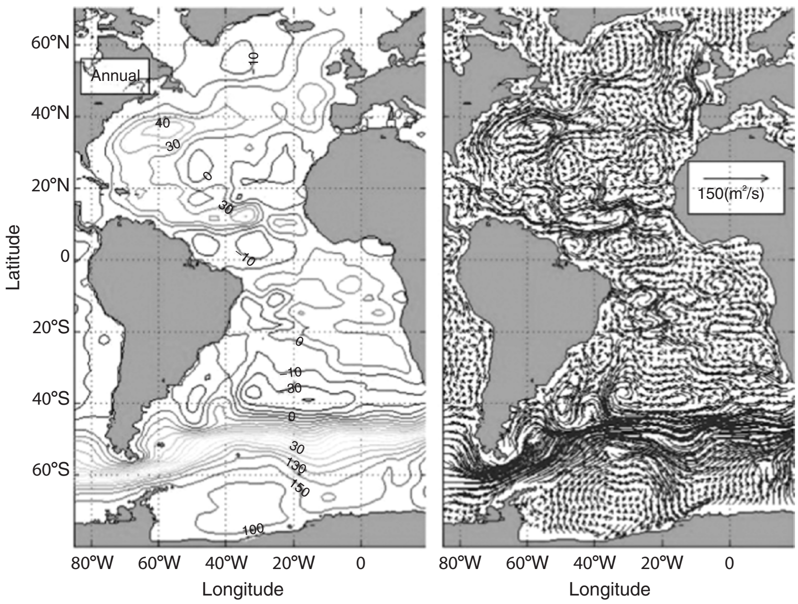

Fig. 12.1. Annual mean volume transport streamfunction (Ψ) and vertically integrated velocity (U, V) for the Atlantic Ocean (from Chu and Fan 2006, Journal of Marine Systems)

Atlantic contains a wealth of important information. More recent atlases of hydrographic data for the Atlantic have been published by Teague et al. (1990), Lozier et al. (1994, 1995), Levitus and Boyer (1994), and Levitus et al. (1994).

Using limited data, Iselin (1936) produced a map of the general circulation of the western North Atlantic Ocean. Later on, Sverdrup et al. (1942) generated a more detailed map of the upper layer transports for the North Atlantic circulation including northern and southern recirculation of the Gulf Stream, crossequatorial flow, Labrador and Irminger Currents, and a subpolar gyre. Stommel (1957) presented two-layer circulation for the entire Atlantic Ocean, contained in the similar, but observationally based, maps of Worthington (1976), Wunsch (1978, 1996), Wunsch and Grant (1982), Schmitz and McCartney (1993), Schmitz (1996a), and Olbers et al. (1985).

Worthington (1976) constructed the volume transport streamlines for the North Atlantic Circulation. In his calculation, the intergyre and interbasin exchanges are found overly restrictive within the North Atlantic and between the South and North Atlantic Ocean (Clark et al. 1980; Schmitz and Richardson 1991; Schmitz 1996a). Schmitz and McCartney (1993) presented an updated version of a transport schematic representation for the upper larger general circulation of the North Atlantic Ocean (0–800 m in the subtropical gyre; temperature >7°C say) and for some selected deep currents (~2,000−4,000 m depth, say).

One feature of the "update" involves a modified path (Reid 1994; Tschiya 1989) for Mediterranean Water (∼1 Sv at the source according to Bryden and Kinder 1980), which entrains at least 1 Sv from the ambient water present as it plunges down the slope so that the net circulation (Price and Baringer 1994) is at least 2 Sv. Chu and Fan (2006) calculated volume transport stream function for the global oceans (see Chap. 7) from surface wind and hydrographic data.

US Naval Oceanographic Office produced a composite smoothed speed contour and direction (arrow) plot of the surface currents in the North Atlantic, based on one particular set of ship drift data (Fig. 12.2). Major circulation features of the upper layer flow in the North Atlantic Ocean are represented in Fig. 12.2 such as a strong Gulf Stream, double gyre structure (subtropical and subpolar gyres), crossequatorial current, and North Atlantic Current with flow into the polar seas as is the upper layer transports for the North Atlantic circulation. However, several important characteristics of the upper layer circulation (basically those on smaller spatial scales) are not clearly present in Fig. 12.2. Examples would be the northern and southern recirculation gyres of the Gulf Stream, although there is an Antilles Current in Fig. 12.2.

The P-vector method is used (Chu 1995a) to calculate three-dimensional absolute velocity from NOAA's climatological temperature and salinity data. Many of the major circulation features of the upper layer flow in the North Atlantic Ocean are contained in the inverted velocity field at 500 m depth (Fig. 11.3). The circulation pattern is dominated by a strong Gulf Stream

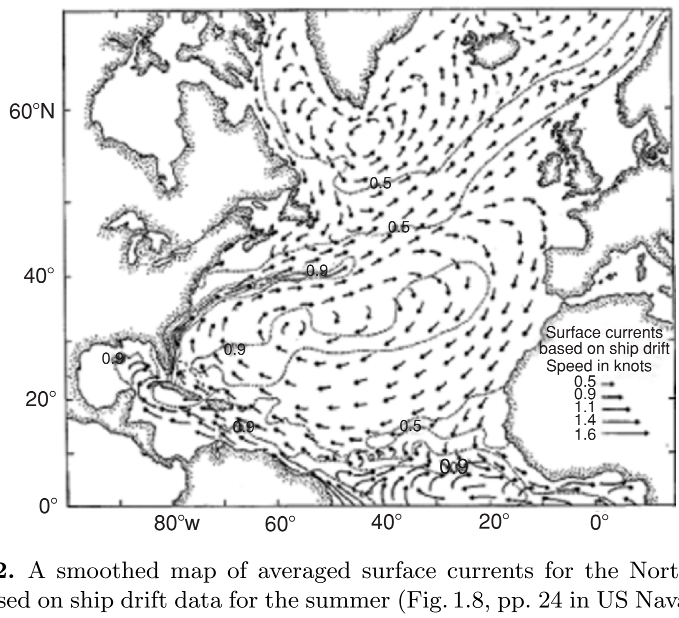

Fig. 12.2. A smoothed map of averaged surface currents for the North Atlantic Ocean based on ship drift data for the summer (Fig. 1.8, pp. 24 in US Naval Oceanographic Office Publ. 700, 1965). *Arrows* indicate flow directions; *contours* indicate current speed (magnitude, in knots)

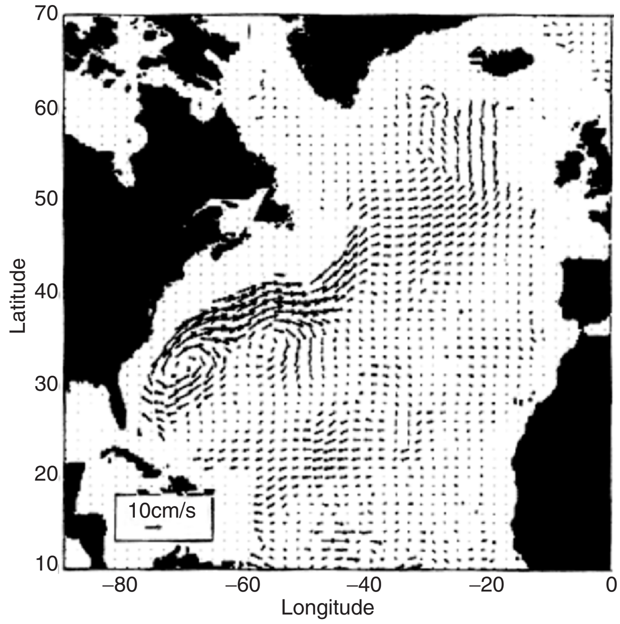

Fig. 12.3. Horizontal absolute velocity vector at 500 m depth calculated, using the P-vector method (after Chu 1995a, Marine Technology Society Journal)

leaving the North American coast at about 35°N, turning towards east at 38°N, 60°W to a branching point at about 40°N, 40°W, splitting into penetrating into the longitude of the Grand Banks, and some other features. The horizontal velocity field at 500 m depth (Fig. 12.3) displays a circulation pattern in the main thermocline very similar to that obtained by Olbers et al. (1985) using the β-spiral method. The circulation pattern is dominated by a strong Gulf Stream leaving the North American coast at about 35°N, turning towards the east at 38°N, 60°W to a branching point at about 40°N, 40°W4, splitting into two branches. The northern branch moves the water in the northeastward direction until reaching 50°N and deflects towards north at 50°N, 15–30°W. The width of this branch increases to the northeastward from 700 km at 40°N, 50°W to nearly 1,500 km in the northeast Atlantic at 50−60°N, 15−30°W.

The southern branch moves the water to the southeastward direction between 30°N and 35°N toward Gilbratar, and feeds into the subtropical gyre. The velocity calculated using the P-vector method also shows a tight recirculation cell on the western side of the subtropical gyre which was depicted in earlier research (e.g., Stommel and Scott 1977; Olbers et al. 1985). Furthermore, a northern cyclonic gyre exists, but is much weaker than the subtropical gyre.

The vertical velocity is computed by

$$w = \gamma(x, y, z) P_z(x, y, z). \tag{12.1}$$

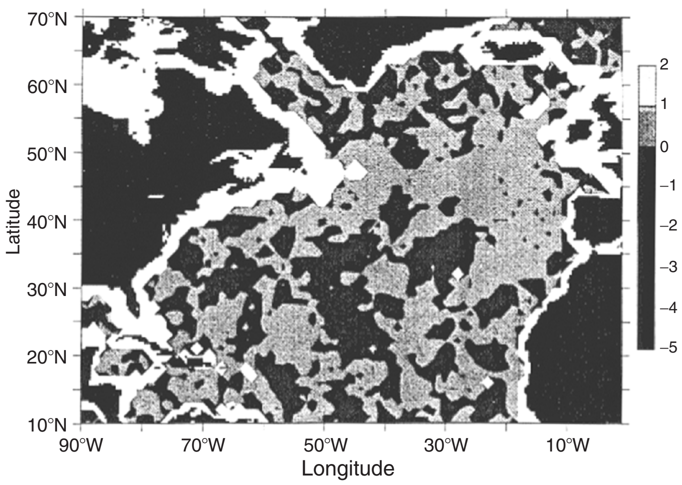

Fig. 12.4. Vertical velocity at 500 m depth calculated using the P-vector method (from Chu 1995a, Marine Technology Society Journal)

Figure 12.4 shows the w-field at 500 m depth. In the vast areas of the North Atlantic Ocean, the vertical velocity is quite weak (less than 1 m day^{-1}) and noisy except in a very small area south of Iceland, where a very strong downward velocity (>4 m day^{-1}) is found. This coincides with the strong downward branch of the global conveyor belt (Broecker 1991). In the subtropical gyre, the water is usually downwelling. This indicates that the P-vector method has the capability to diagnose the vertical velocity.

12.1.2 Circulation at Different Depths

Figure 12.5 shows the absolute velocity vectors at different levels that is calculated by using the P-vector method. The flow pattern at 100 m level (Fig. 12.5a) is quite similar as that at 500 m level: the Gulf Stream, an anticyclonic subtropical gyre, a weak northern cyclonic gyre. A comparison between Figs. 12.3 and 12.5a leads to the fact that the subtropical gyre shrinks in its north–south extension with increasing depth, which agrees with Olbers et al.'s (1985) results. The flow pattern at deep oceans (2,500, 3,500, and 4,500 m levels) is shown in Fig. 12.5b–d. The dominant features at 2,500 m level (Fig. 12.5b) are the western boundary currents. After passing the Gibbs fracture zone at about 50°N, 40°W the current splits into two branches: a weak northern branch and strong southern branch. The southern branch flows in the southwestward direction, turns westward at 40°N 50°W, and then follows around the east coast of North America. As this branch enters the Sagasso Sea Trench, a noticeable cyclonic eddy appears at 4,500-m level (Fig. 12.5d) to conserve the potential vorticity as the ocean depth increase. The maximum swirl speed is 0.02 m s^{-1}. After passing 30°N, the mid-depth flow at the 2,500 m and 3,500 m (Fig. 12.5c) levels recirculates northeastward at 30°N, 70°W with

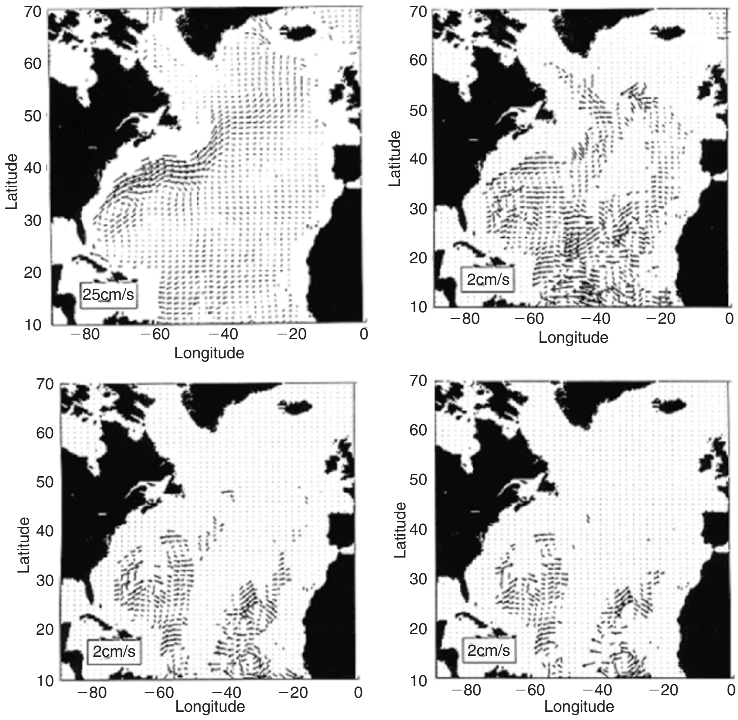

Fig. 12.5. Absolute velocity vectors at different levels calculated, using the P-vector method (from Chu 1995a, Marine Technology Society Journal)

a typical speed that is different from the β-spiral method. Our solution does not show a strong southeastward flow near Bahamas carrying water into the South Atlantic Ocean.

A cyclonic–anticyclonic pair is found in the deep water at the eastern (20−40°W) tropical part (10−30°N) of the North Atlantic Ocean. The cyclonic eddy is in the south, and the anticyclonic eddy is in the north. The maximum swirl speed is around $0.02\,\mathrm{m\,s^{-1}}$. This feature is indeed, strikingly similar to the map (Defant 1941) of the absolute flow at 2,000 m. Furthermore, this dipole structure becomes more evident as the depth increases.

The absolute velocity computed by Olbers et al. (1985) has less noise at the deep level low latitudes than the P-vector method. This is partly because the turbulence fluxes and associated mixing are neglected in the P-vector computation.

12.1.3 Vertical Cross Sections

To compare the results from this method with the other inverse methods such as the box method (Wunsch 1978; Wunsch and Grant 1982) and the β-spiral

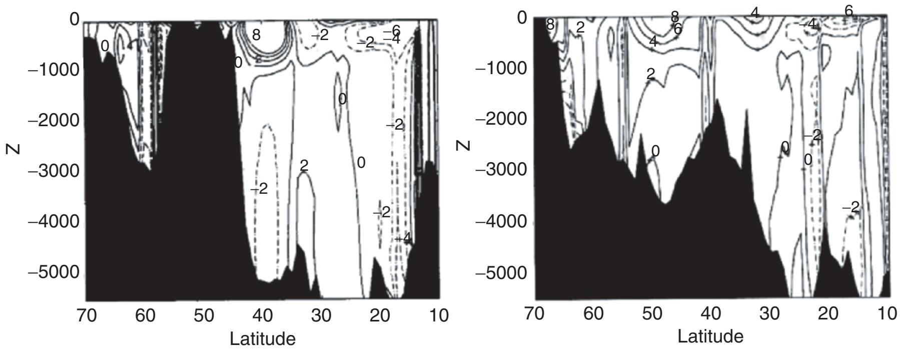

Fig. 12.6. Absolute u-velocity (unit: $\text{cm}\,\text{s}^{-1}$) along (**a**) 57°W, and (**b**) 30°W, calculated, using the P-vector method (from Chu 1995a, Marine Technology Society Journal)

method (Olbers et al. 1985), we display the longitudinal cross sections of u-velocity along 57 and 30°W (Fig. 12.6) and the latitudinal cross sections of v-velocity along 24°N (and 53°N and 59°N (Fig. 12.7).

The main features in the western (Fig. 12.6a) and eastern parts (Fig. 12.6b) of the subtropical gyre are (a) a strong upper ocean (above 1,000 m depth) eastward flow (the Gulf Stream) between 30 and 40°N with a maximum speed greater than $0.20\,\text{m}\,\text{s}^{-1}$, (b) a weak westward flow below the Gulf Stream (western boundary currents), (c) a near surface westward flow south of 30°N (southern branch of the subtropical gyre) with a maximum speed of $0.06\,\text{m}\,\text{s}^{-1}$, and (d) banded structure in the deep layers ($z < -1{,}500\,\text{m}$), where the current direction alternates on a horizontal scale around 2,000 km, which is wider than the Wunsch and Grant (1982) results.

Interesting features are found in the meridional flow at different latitudes (24°N, 36°N, 53°N, 59°N), which is summarized as follows. (a) In the upper ocean (above 1,000 m), at 24°N (Fig. 12.7a) a narrow northward flow appears near the east coast of North America (the Gulf Stream) from 65 to 75°W, with the maximum speed around $0.05\,\text{m}\,\text{s}^{-1}$ and the width near 1,000 km, and a weaker returning southward flow occupies the rest of the region $(65 - 20°\text{W})$.

At the latitude of 36°N (Fig. 12.7b), a narrow southward flow appears between 60 and 70°N and is sandwiched between two northward flows. This indicates the existence of a recirculation cell at that latitude (36°N). The core of the northward flow shifts towards east as the latitude increases (Fig. 12.7c, d): the maximum current speed appears between longitudes 20−30°W. (b) In the deeper layer (below 1,000 m depth), a banded structure reveals the alternating northward and southward flow with smaller current speed. The width of these alternating bands is around 1,000–2,000 km, which is also wider than the results of Wunsch and Grant (1982).

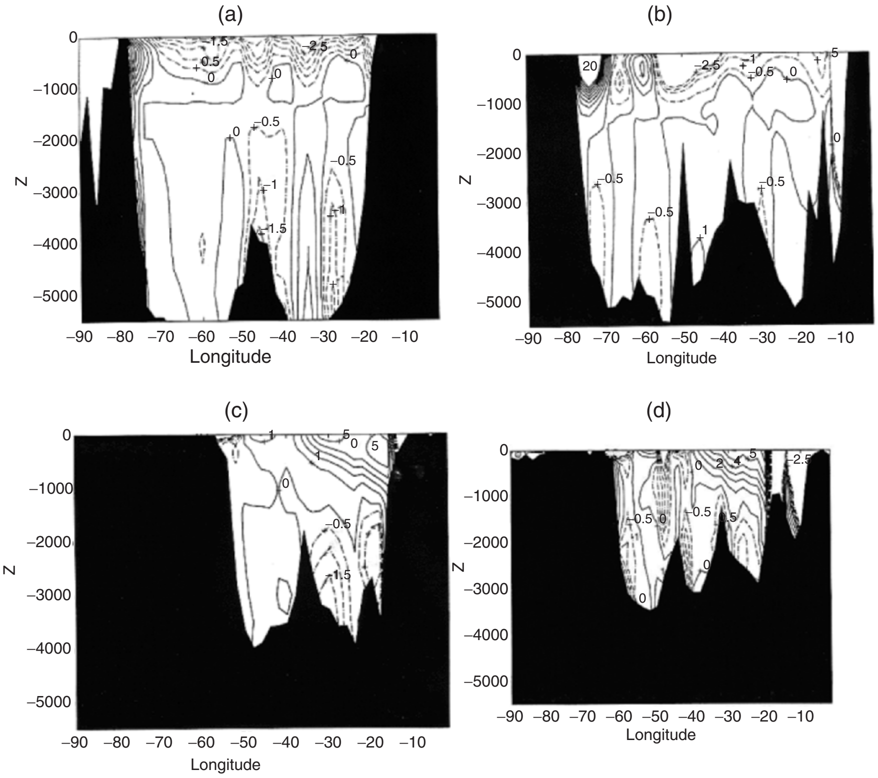

Fig. 12.7. Absolute v-velocity (unit: $\mathrm{cm\,s^{-1}}$) along (**a**) 24°N, (**b**) 36°N, (**c**) 53°N, and (**d**) 59°N, calculated using the P-vector method (from Chu 1995a, Marine Technology Society Journal)

12.1.4 Gulf Stream Volume Transport

As the Florida Current leaves the Blake Plateau and becomes the Gulf Stream, this western boundary current turns from predominantly meridional to mostly zonal, near the Cape Hatteras and beyond. This separation of the Gulf Stream from the coast is a challenging problem.

The Gulf Stream volume transport has been estimated by many authors. The volume transport stream function (Ψ) can be calculated using the method described in Chap. 8. Difference of Ψ-value between the North Atlantic continent and at the center of the subtropical gyre is used to quantify the volume transport of the Gulf Stream. The monthly mean Gulf Stream transport is quite steady with a maximum transport of 62 Sv in October and a minimum of 52 Sv in March and April (Fig. 12.8). The calculated Gulf Stream volume transport (57 Sv) is weak compared to the value of 120 Sv found after detachment from Cape Hatteras when encompassing the Southern Recirculation gyre transport (Hogg 1992). This is due to the smoothed nature of the climatological wind and hydrographic data used.

12.2 South Atlantic Ocean Circulation

From its littoral margin to the open ocean, the western South Atlantic is marked by the circulation patterns and exchange processes that are centrally important to the regional marine resources and local economics, and equally important to the global flux of heat and dissolved substances (Campos et al. 1995). The depth-integrated western boundary current (Brazil Current) originates from the South Equatorial Current (Fig. 12.1). A major change in the flow patterns along the western boundary occurs in the southern Brazil Basin. Among other important characteristics, the Southwest Atlantic is characterized by the presence of the Brazil Current (a warm western boundary current), Brazil–Malvinas confluence, subtropical gyre, and Benguela Current (an eastern boundary current).

The Brazil Current is a weak western boundary current (weaker than its counterpart in the North Atlantic – the Gulf Stream) carrying warm sub-

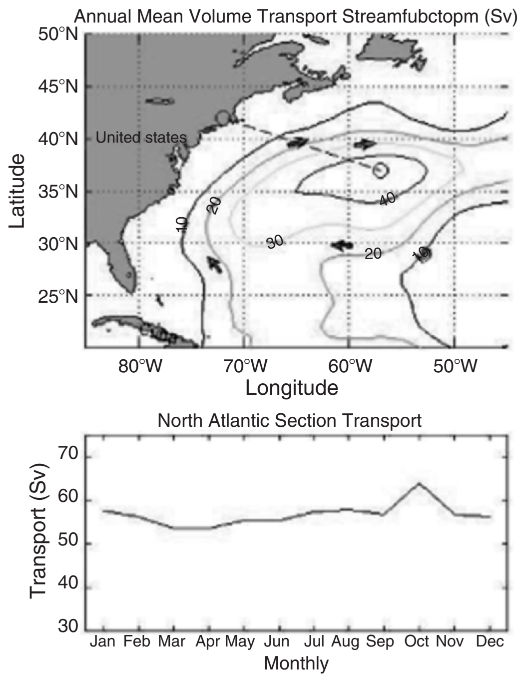

Fig. 12.8. The inverted monthly volume transport between the North American east coast and the center of the subtropical gyre representing the Gulf Stream transport (Chu and Fan 2006, Journal of Marine Systems)

tropical water, which runs south along the coast of Brazil from about 9°S to about 38°S and is generally confined to the upper 600 m of the water column. Its origin begins where the westward flowing trans-Atlantic South Equatorial Current bifurcates (or splits) as it approaches the continental shelf off the coast of Cabo de Sao Roque, Brazil (Stramma et al. 1990; Podesta et al. 1991). The South Equatorial Current water flowing north becomes the North Brazil Current, and the branch flowing south becomes the Brazil Current. The Brazil Current begins at about 10°S, separating slightly from the coast near 12°S where the continental shelf becomes wider (Stramma et al. 1990; Peterson and Stramma 1991). The Brazil Current continues to flow south off the Brazilian coast until it reaches about 33−38°S, where it collides with the north-flowing Malvinas (Falkland) Current. Gordon and Greengrove (1986) first defined this region the Brazil–Malvinas Confluence.

Olson et al. (1988) and Podesta et al. (1991) analyze satellite images (1984–1987) and show that the actual point at which the Brazil Current separates from the continental shelf varies anywhere between 33 and 38°S, with the average being about 36°S. The Brazil Current is then, in part, deflected to the east, off-shore of Rio de la Plata, a region known as the Brazil–Malvinas Confluence Zone – one of the most energetic regions in all the oceans (Sarceno et al. 2004).

Comparing to its counterpart in the Northern Atlantic (i.e., the Gulf Stream), the transport of the Brazil Current is weak. In its northern part, this current is shallow and closely confined to the continental shelf. This causes difficulty in estimating the transport of the Brazil Current. Figure 11.9 shows the inverted monthly mean volume transport stream function Ψ, and vertically integrated velocity (U, V) (see Chap. 8) in the western side of South Atlantic Ocean. The volume transport of the Brazil Current is approximately 10 Sv.

The upper layer (500 m) transport is estimated to be 5 and 6.5 Sv around 20°S (Peterson and Stramma 1991; Stramma et al. 1990). At about 20.5°S, a cyclonic gyre seaward of the Brazil Current centered at about 17°S and 34°W has been observed, and attributed to the southernmost meanders of the South Equatorial Current that are reflected northward by this same seamount chain (Memery et al. 2000; Stramma et al. 1990). This pattern is also identified in the inverted global (Ψ, U, V) fields (Fig. 12.9). At about 20.5°S, near the seamount chain, the current velocity is estimated to be about $0.5-0.6\,\mathrm{m\,s^{-1}}$ by Evans et al. (1983).

As the Brazil Current flows south of 24°S, it intensifies by about 5% per 100 km, which is similar to the growth rate in the Gulf Stream, although transport values in the Brazil Current are considerably less (Peterson and Stramma 1991). Thus, at about 33°S the total transport (which includes a recirculation cell in the upper 1,400 m) is about 18 Sv, and reaches the values from 19 to 22 Sv at about 38°S, where it encounters the Malvinas (Falkland) Current (Olson et al. 1988; Peterson and Stramma 1991). The mean latitude of the Brazil Current's separation from the shelf break is about 35.8°S ± 1.1° and

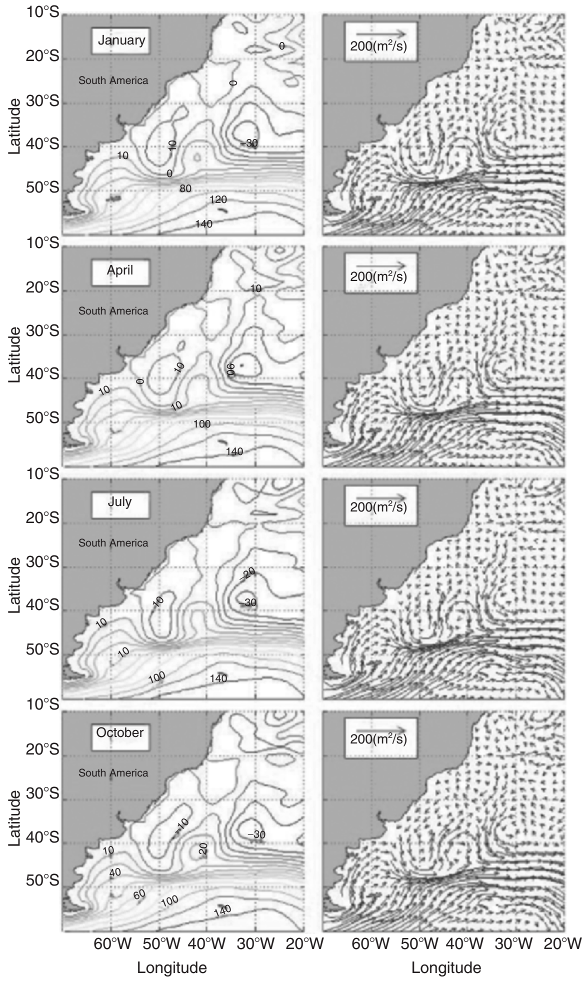

Fig. 12.9. The inverted monthly mean Ψ and (U, V) vector fields in the southwestern South Atlantic Ocean: (**a**) January, (**b**) April, (**c**) July, and (**d**) October (Chu and Fan 2006, Journal of Marine Systems)

for the Malvinas Current, the mean latitude of separation is $38.9°S \pm 0.9°$. The coastal ranges of the separation positions are at 950 and 850 km, respectively (Olson et al. 1988). These features are also identified from the global (Ψ, U, V) fields (Fig. 12.9).

12.3 Brazil–Malvinas Confluence

The combined flow of the two currents causes a strong thermohaline frontal region, called the Brazil–Malvinas Confluence in which the Brazil Current breaks off into two branches, one turning to the north forming a recirculation cell, while the other continues southward and veers northeast at about 45°S, becoming the South Atlantic Current (Fig. 12.9). The mean transport in this region has been measured to be about 11 Sv (Garzoli and Bianchi 1987), which is very similar to the inverted value shown in Fig. 12.9.

Flow can increase up to 23 Sv at the Brazil–Malvinas Confluence (Garzoli and Bianchi 1987). The mean conditions of circulation vary significantly, and more recent evidence shows that they are more or less related to the meteorological anomalies (Assireu et al. 2003). Occasionally, when a meandering Brazil Current that has extended unusually far south retreats, it can shed a series of warm core eddies that migrate into the Antarctic Circumpolar Current (Partos and Piccolo 1988). The values also vary according to the measurement method and depth.

The range of the Brazil–Malvinas Confluence oscillate between 54 and 45°W, a total distance of about 770 km (at 38°S). The meanders appear to occur on a 12 month cycle and are likely to correlate to changes in the separation latitude of the Brazil Current (Boebel et al. 1999; Garzoli and Bianchi 1987; Goni and Wainer 2001; Maamaatuaiahutapu et al. 1999; Zavilov et al. 1999). The mean speed of the front is estimated to be about $0.14\,\mathrm{m\,s^{-1}}$. The front oscillates around its mean seasonal position (farther north and east during austral winter and farther south and west during austral summer) within a period of about one month and amplitude that varies from 10 to $50\,\mathrm{km\,day^{-1}}$. The mean velocity of the displacement of the front reaches values up to $10\,\mathrm{km\,day^{-1}}$ (Garzoli and Bianchi 1987). This area is also rich in eddies, more often called Brazil Current Rings, averaging to about 7–9 rings per year. These elliptical rings can vary in size from about 56 to 225 km along the semimajor axis, and 23–108 km for the semiminor axis. These anticyclones have a mean lifetime of about 35 days and translational speeds of anywhere between 4 and $27\,\mathrm{km\,day^{-1}}$ (Lentini et al. 2002). On an average, the temperature in the Brazil Current is about $18-28$°C, with essentially three meridional zones that experience several degrees of distinctly different annual temperature fluctuations, which correspond to their proximity to the shore. The first zone is located over the shelf and experiences temperature variability of 7–10 degrees, which is controlled by both the winter invasions of sub-Antarctic water from the Malvinas Current and discharges from Rio de la Plata and Patos-Mirim. The second or central portion, closer to the eastern margin of the continental shelf, experiences a 5–7 degree variance. The third, on the seaward-most zone, shows little fluctuation up to the Confluence (Memery et al. 2000; Zavilov et al. 1999). Temperatures in the southern section of the current, near the Confluence, can change by 5–13 degrees, with the cooler temperatures occurring around August–September and the warmer values observed in February (Boebel et al. 1999; Podesta et al. 1991). Almost yearly temperature anomalies of warm and cold fronts occur that seem to be related to the El Nino-Southern Oscillation (ENSO) events. Anomalous cold water extensions to the north occur on the shelf generally 1 year after every warm ENSO event, and anomalous warm water extensions occur generally 1 year after every cold ENSO (Lentini et al. 2001).

Surface salinities indicative of Brazil Current waters range from 35.1 to 36.2 ppt, with the maximum commonly found at around 20°S, where it can reach a salinity of 37.3 ppt (Memery et al. 2000; Wilson and Rees 2000). Although that is energetically comparable to its North Atlantic counterpart, particularly in the region of confluence with the northward-flowing Malvinas Current at approximately 38°S, while the salinity is weaker than the Gulf Stream in terms of the mass transport (Fig. 12.9). The western limb of the recirculation cell (anticyclonic) separates from the continental slope at about 38°S upon its confluence with the northward-flowing Malvinas Current, whereupon the bulk of the Malvinas retroflects cyclonically (clockwise) back towards the southeast while the lesser portions continue northeast along the coast. On the eastern side of the cyclonic trough is the combined southeastward flow of Malvinas and Brazil Current waters that extend to 45°S before the subtropical waters turn east and north to form the pole-ward limits of the subtropical gyre. The Malvinas waters continue south to the southern margin of the Argentine Basin (49°S) before turning east with the Antarctic Circumpolar Current regime. Our results are consistent with the earlier studies (e.g., Peterson and Whitworth 1989). The Brazil–Malvinas confluence occurs all year round with a very weak seasonal variability.

Questions and Exercises

(1) What are the major characteristics of the North Atlantic Ocean circulations at various depths? Compare the inverted velocity fields to that calculated by other authors.

(2) The monthly mean Gulf Stream volume transport is estimated from the WOA (T, S) data using the P-vector inverse method (Fig. 12.8) with weak seasonal variation (maximum value of 62 Sv in October and minimum value of 52 Sv in March and April). Is it realistic? Why?

(3) Brazil–Malvinas Confluence is an important feature of the western boundary currents in the South Atlantic. Discuss the major characteristics of the Brazil–Malvinas Confluence and its impact on the global climatic systems.

(4) Select an area with your interest. Download the P-vector inverse codes for calculating the absolute velocity at z- and isopycnal-coordinate systems from the DVD-ROM. Run these codes using the WOA or GDEM (T, S) data to get absolute velocity. Discuss the major characteristics of the circulation in the area including the seasonal variation, causes of these features, and the effect of the circulation on the global system.

(5) Compare your computed absolute velocity with the absolute velocity data stored in the DVD-ROMs.