

Abyssal Circulation of the Atlantic and The Southern Ocean

5 November 2013

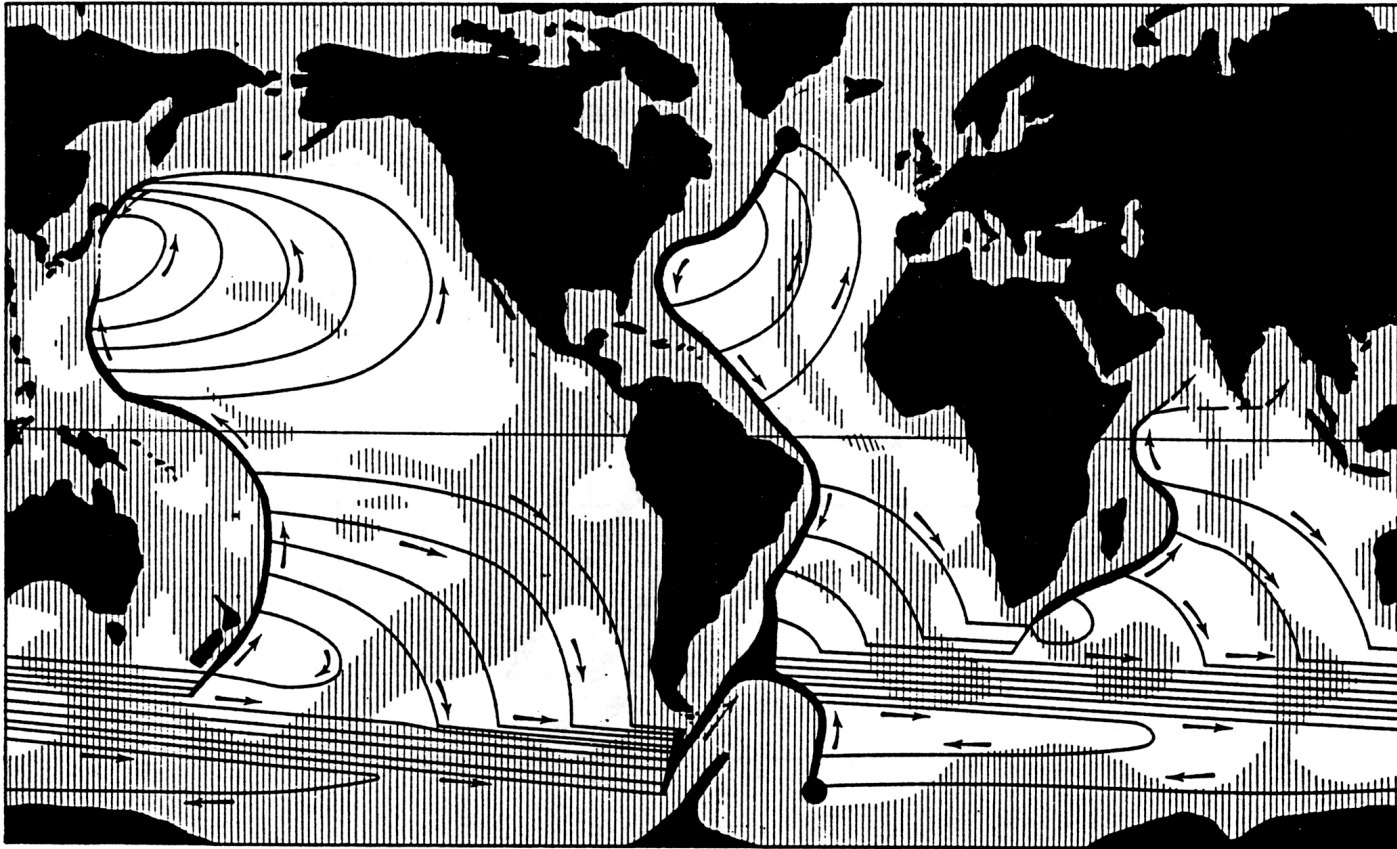


FIGURE 7.16

Global abyssal circulation model, assuming two deep water sources near Greenland and Antarctica (filled circles), filling a single abyssal layer. (These sources are actually at different densities.) *Source: From Stommel (1958).*

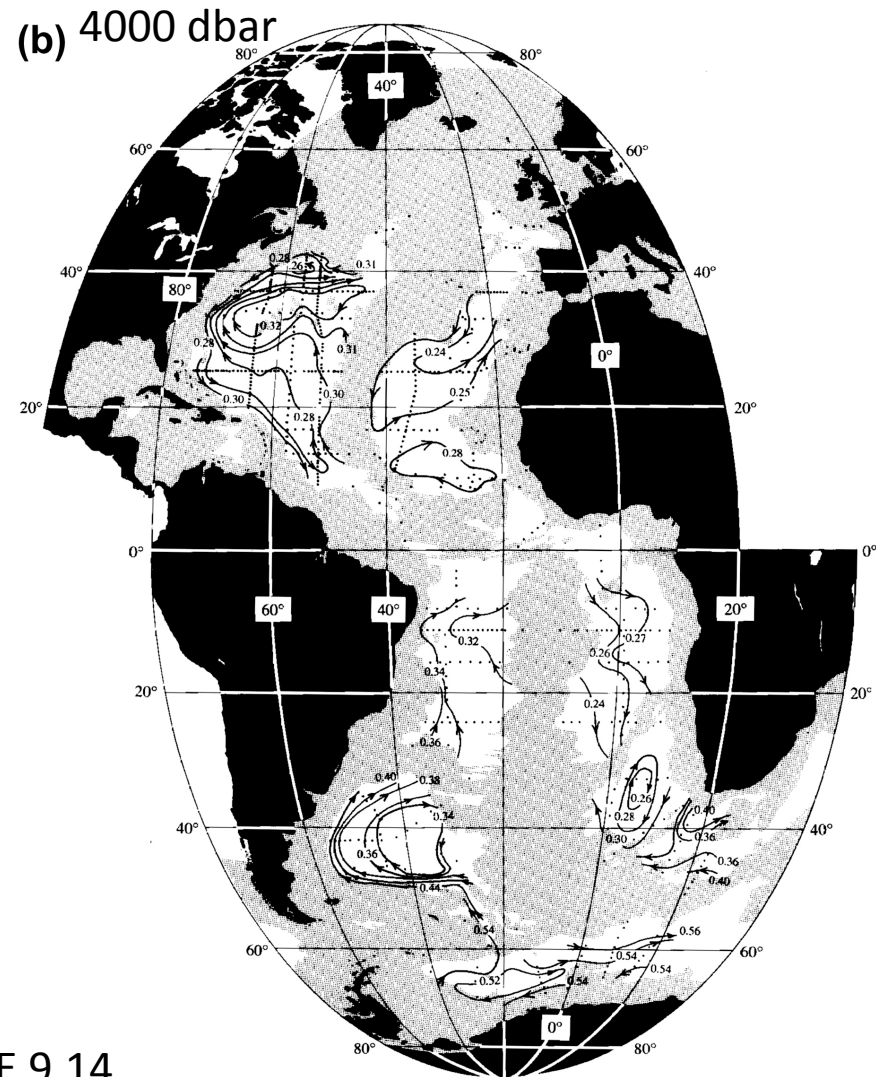
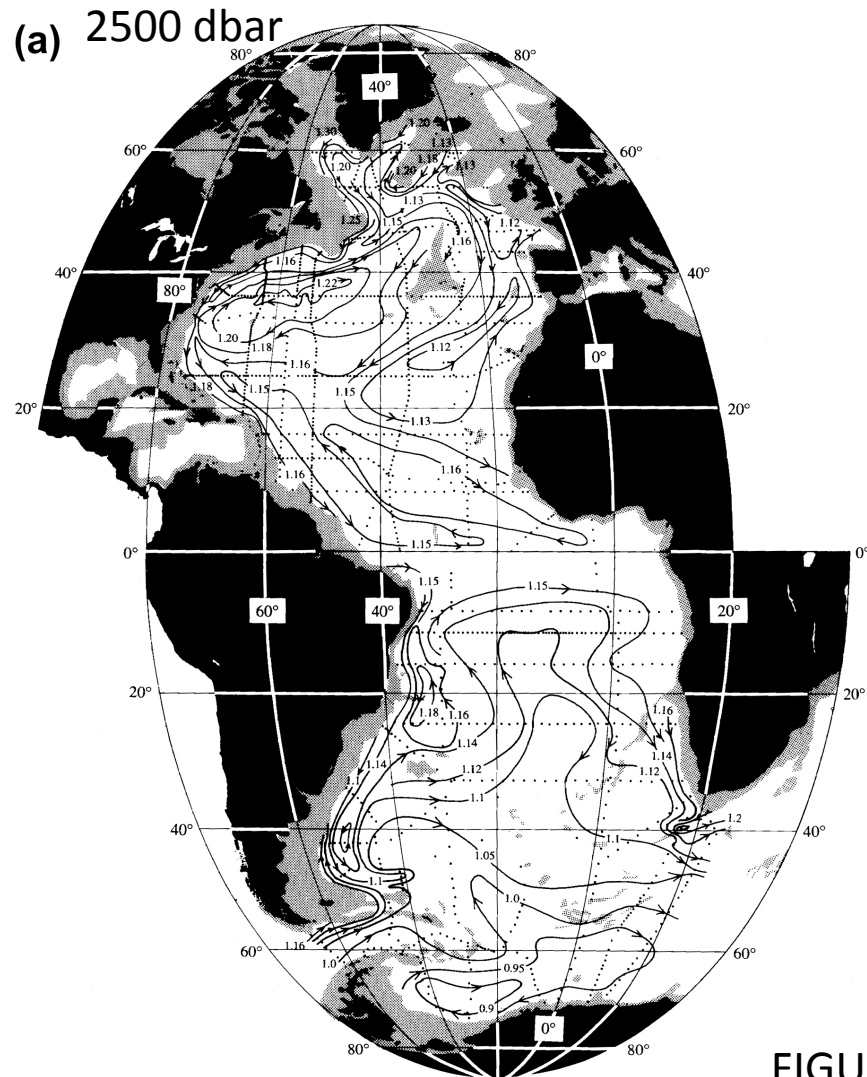


FIGURE 9.14

Steric height ($10 \text{ m}^2 \text{ s}^{-2}$) at (a) 2500 dbar and (b) 4000 dbar, adjusted to estimate the absolute geostrophic circulation. *Source: From Reid (1994).*

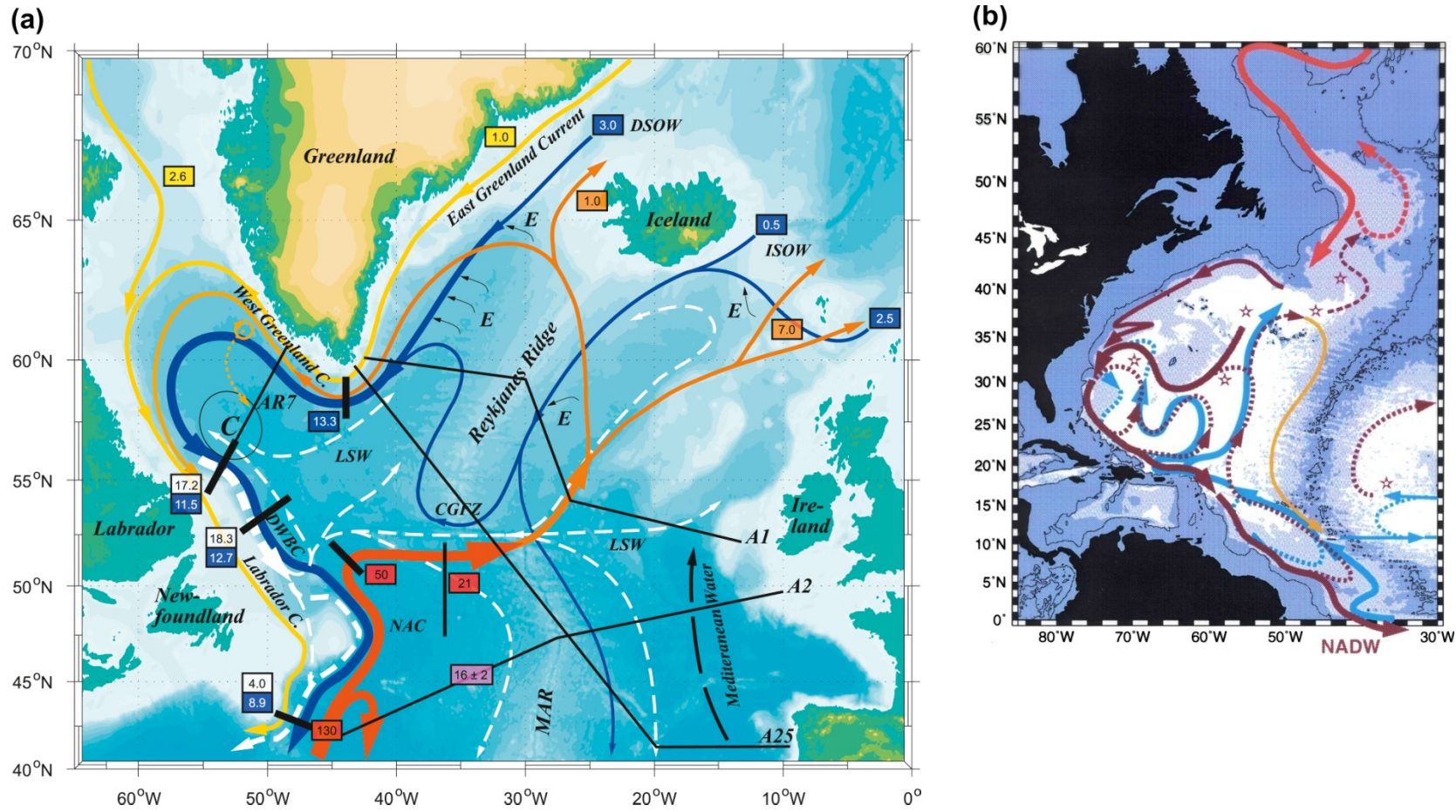
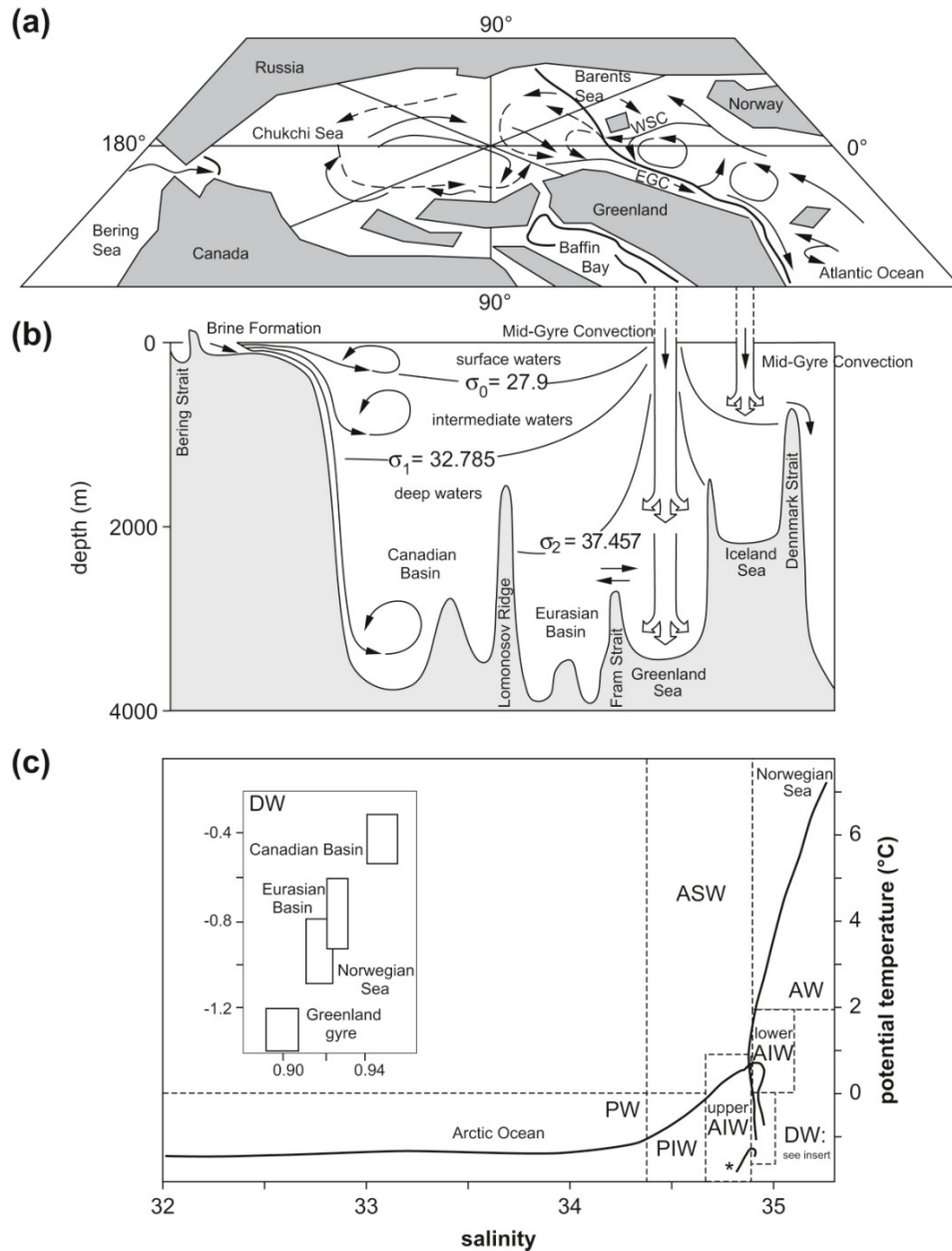


FIGURE 9.15

Schematics of deep circulation. (a) NSOW (blue), LSW (white dashed), and upper ocean (red, orange, and yellow) in the northern North Atlantic. *Source: From Schott and Brandt (2007).* (b) Deep circulation pathways emphasizing DWBCs (solid) and their recirculations (dashed). Red: NSOW. Brown: NADW. Blue: AABW. This figure can also be found in the color insert. (*M.S. McCartney, personal communication, 2009.*)



Overall schematic of (a) circulation, (b) water mass layers and transformation sites, and (c) water masses in potential temperature-salinity. Deep convection in the Greenland Sea in (b) has been replaced by mid-depth convection since the 1980s. Acronyms in (a): EGC, East Greenland Current; WSC, West Spitsbergen Current. Acronyms in (c): AW, Atlantic Water; AIW, Arctic Intermediate Water; ASW, Arctic Surface Water; DW, Deep Water; PIW, Polar Intermediate Water; PW, Polar Water. *Source: From Aagaard, Swift, & Carmack (1985); amended by Schlichtholz and Houssais (2002).*

FIGURE 12.2

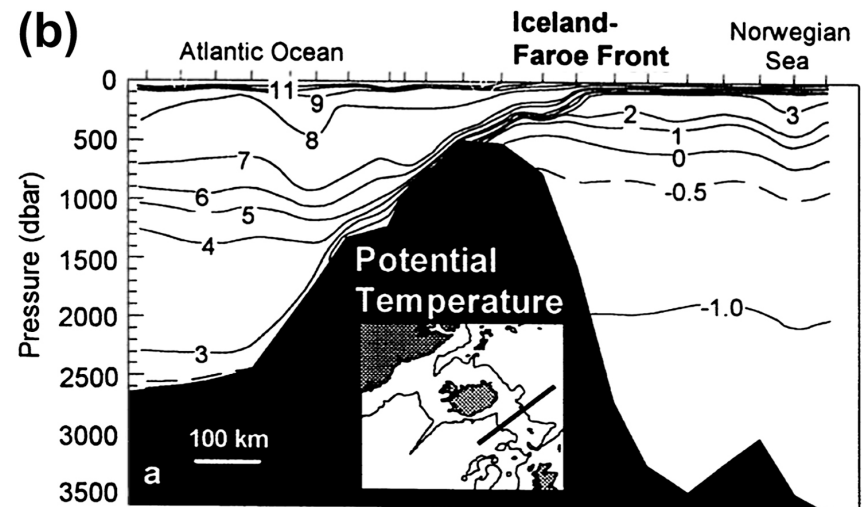
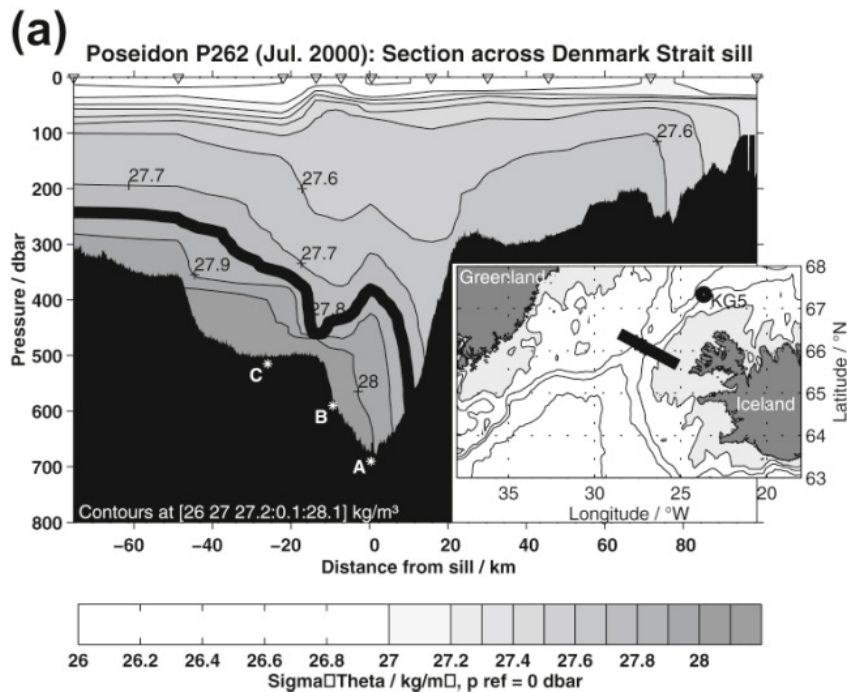
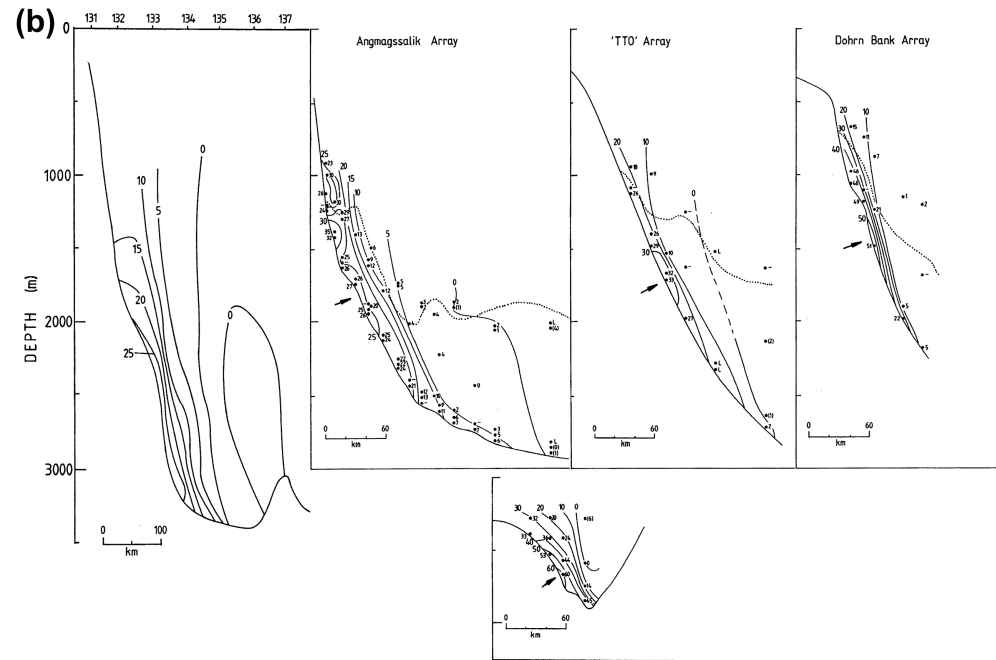
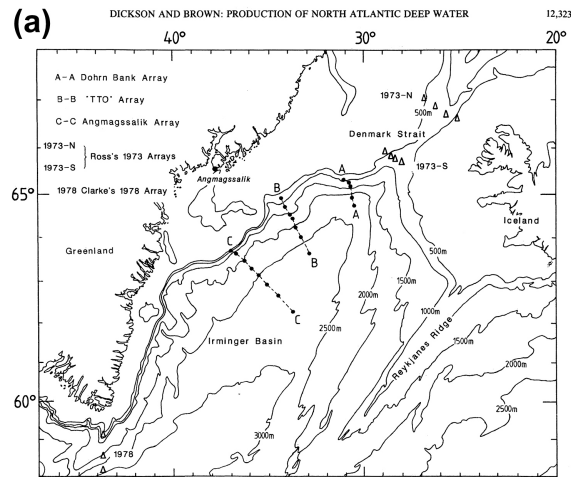


FIGURE 9.24

(a) Potential density in Denmark Strait. The heavy contour marks the upper bound on the overflow layer in the strait. *Source: From Macrandar et al. (2005).* (b) Potential temperature (°C) crossing the Iceland-Faroe Ridge. *Source: From Hansen and Østerhus (2000).*



Mean velocities from current meter deployments in Denmark Strait and along the coast of Greenland from 1986 to 1991. Left to right: Cape Farewell (southern tip of Greenland), 63, 64, and 65° S. Small inset at bottom: just south of the strait. The map shows the location of each line of moorings. *Source: From Dickson and Brown (1994).*

FIGURE S9.20

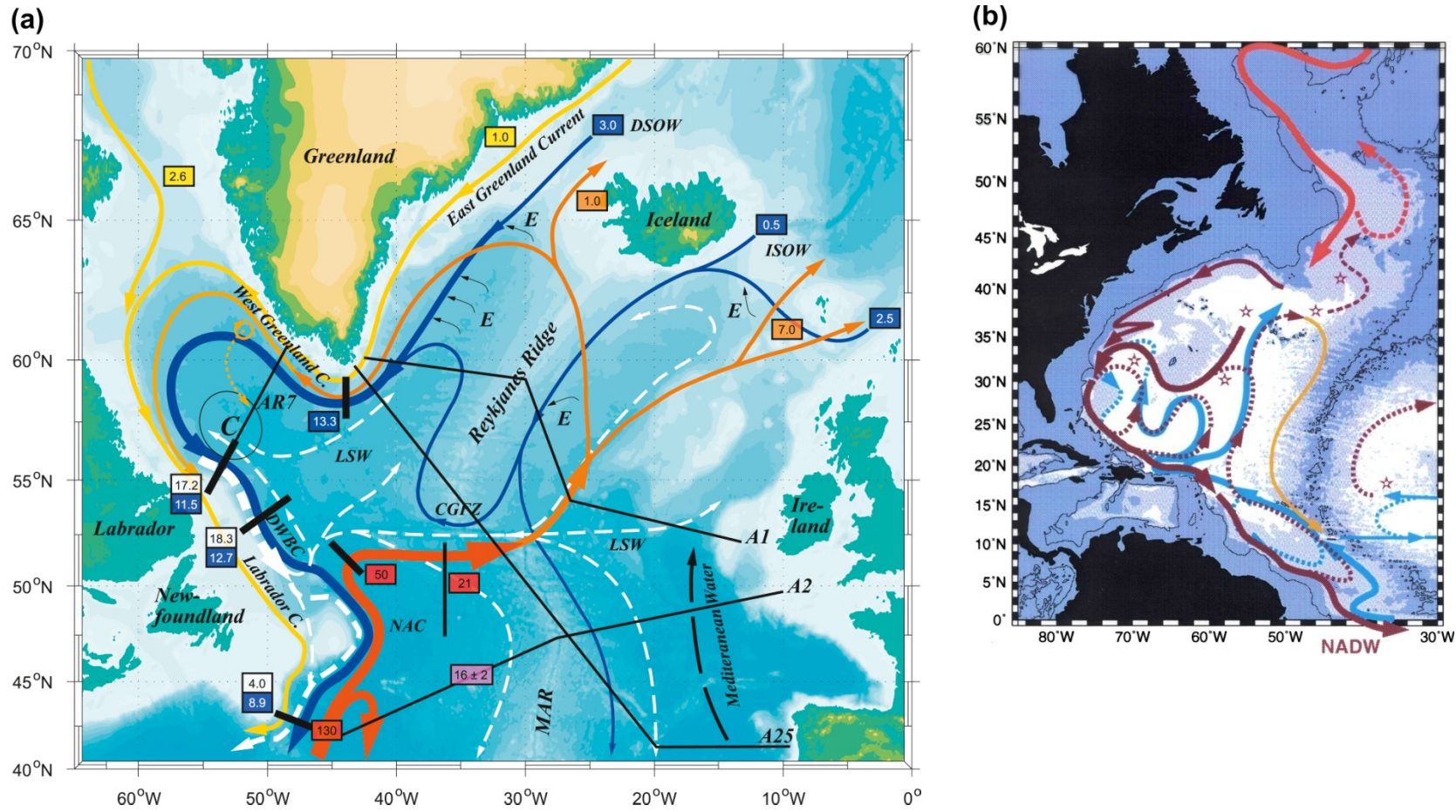


FIGURE 9.15

Schematics of deep circulation. (a) NSOW (blue), LSW (white dashed), and upper ocean (red, orange, and yellow) in the northern North Atlantic. *Source: From Schott and Brandt (2007).* (b) Deep circulation pathways emphasizing DWBCs (solid) and their recirculations (dashed). Red: NSOW. Brown: NADW. Blue: AABW. This figure can also be found in the color insert. (*M.S. McCartney, personal communication, 2009.*)

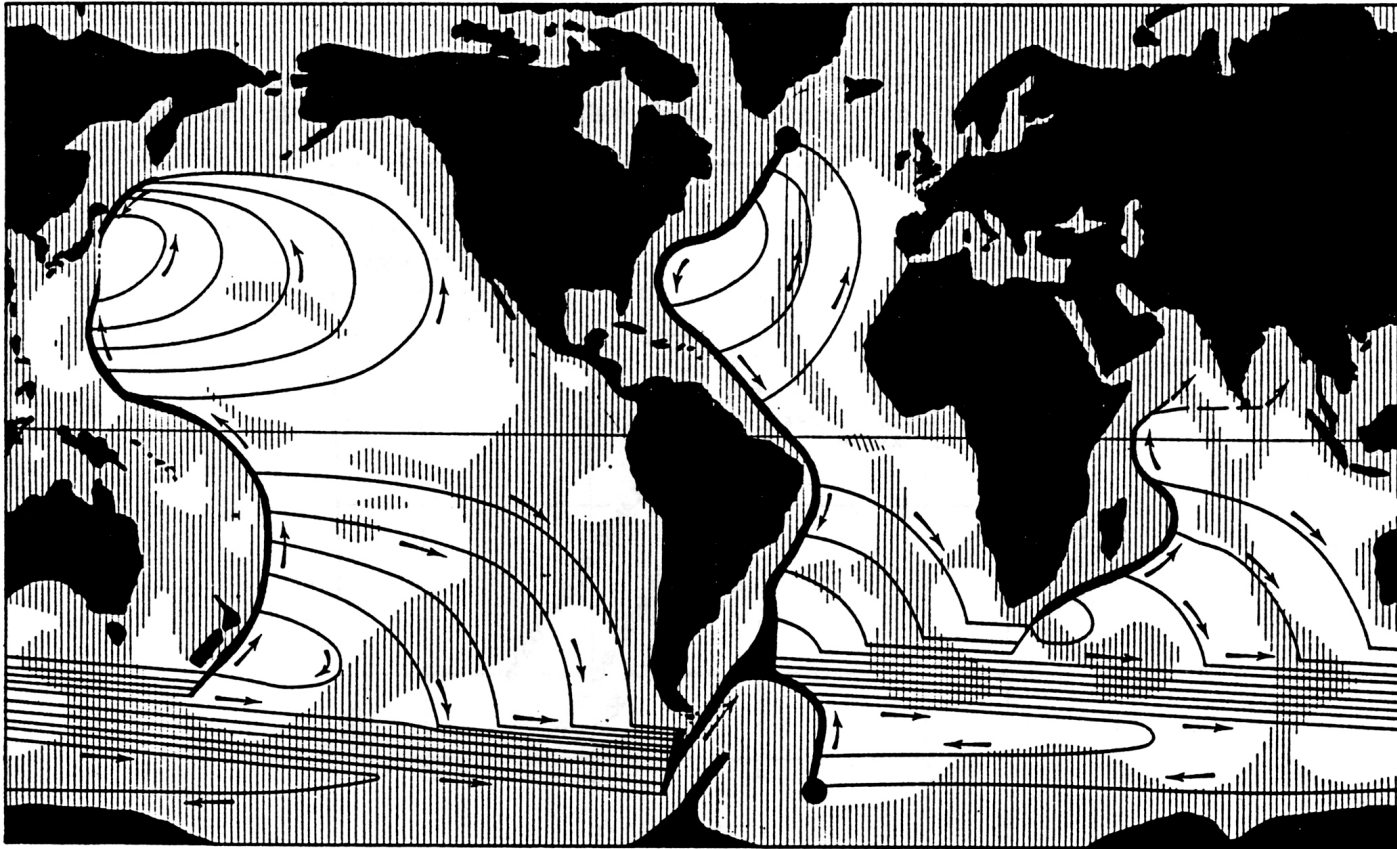


FIGURE 7.16

Global abyssal circulation model, assuming two deep water sources near Greenland and Antarctica (filled circles), filling a single abyssal layer. (These sources are actually at different densities.) *Source: From Stommel (1958).*

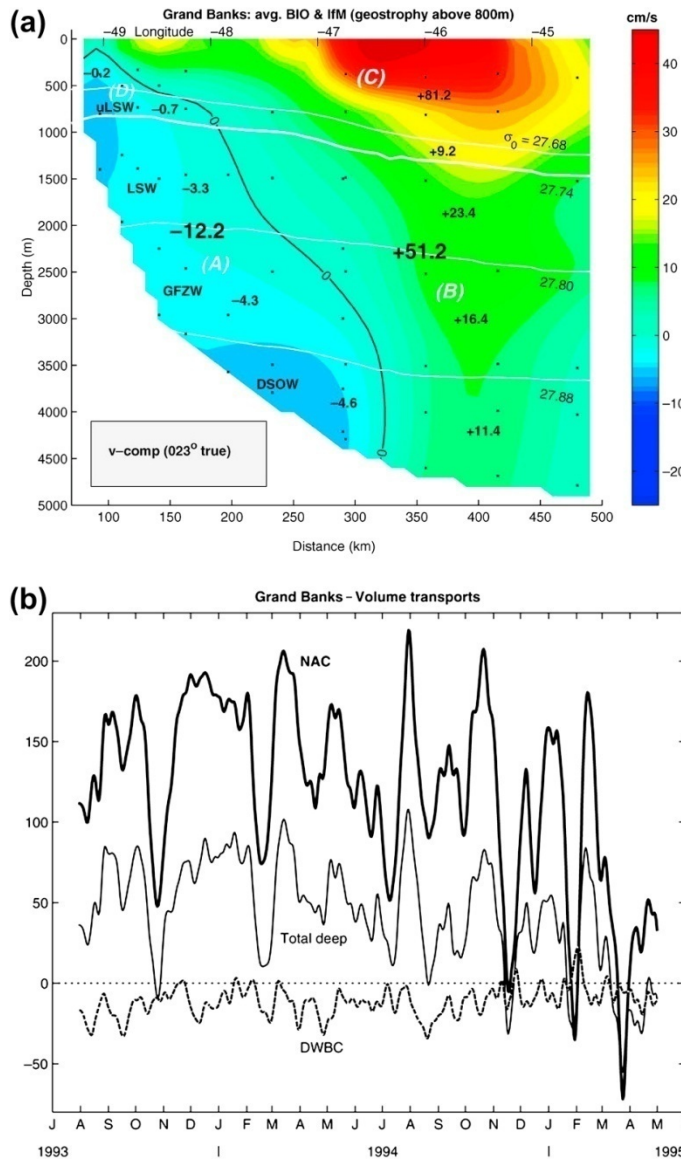
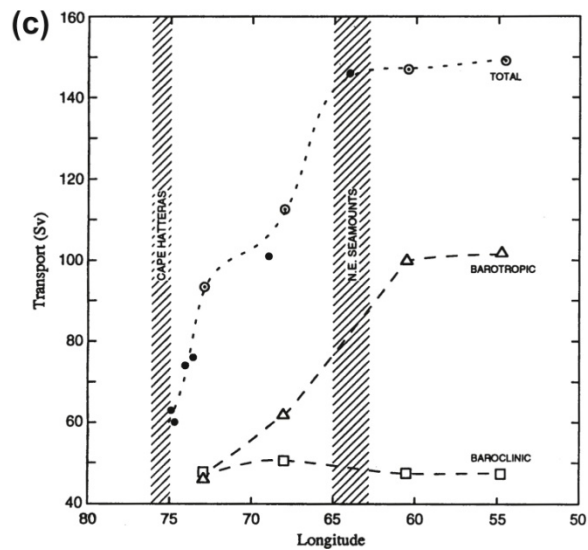
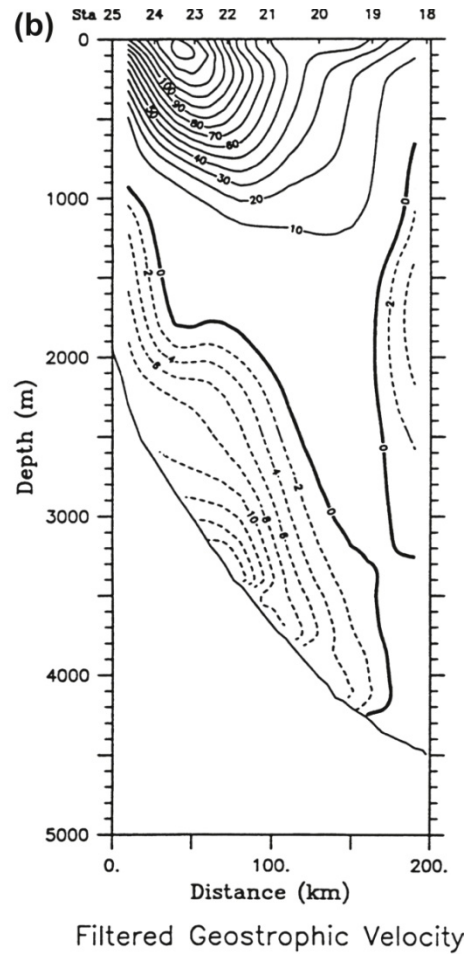
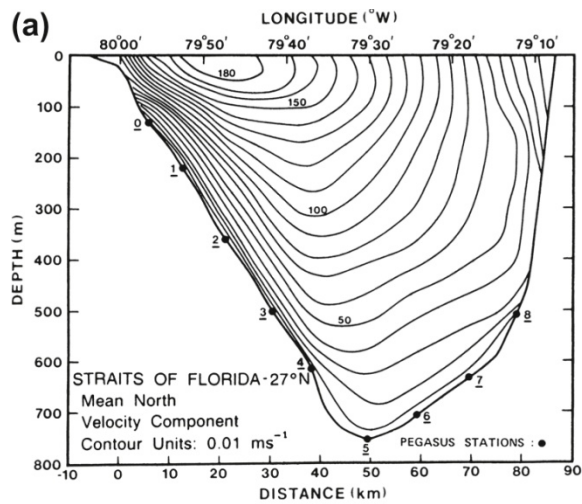


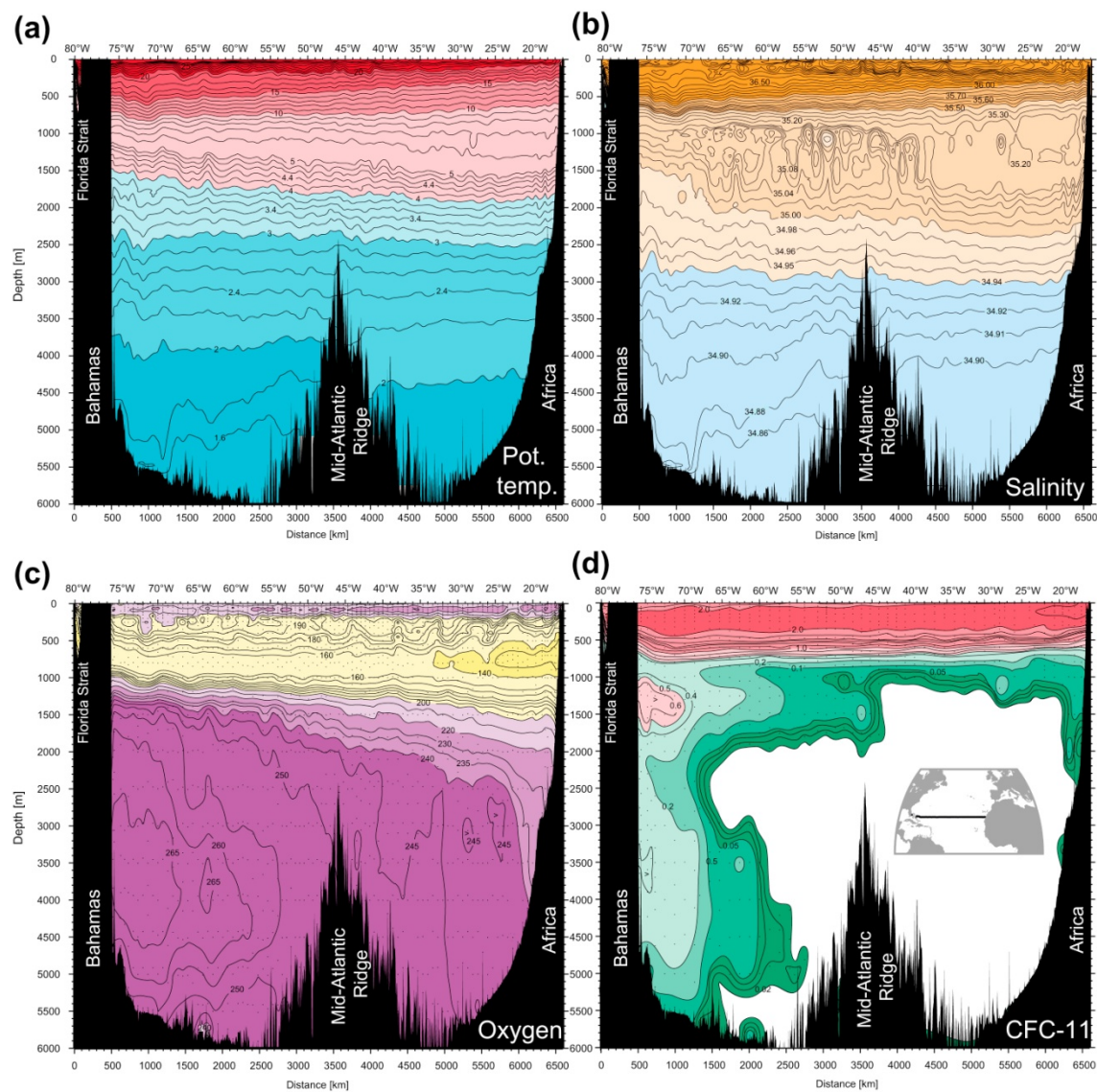
FIGURE S9.21

Deep Western Boundary Current (DWBC) east of the Grand Banks. (a) Mean velocity (color) and transports (numbers in Sv) and (b) transport time series for the DWBC, all deep water and the North Atlantic Current, from current meters at 42°N, 45°W east of the Grand Banks (location in Figure 9.44). Acronyms: LSW, Labrador Sea Water; uLSW, upper LSW; DSOW, Denmark Strait Overflow Water; and GFZW, Gibbs Fracture Zone Water, which is called Northeast Atlantic Deep Water or Iceland Scotland Overflow Water by others. ©American Meteorological Society. Reprinted with permission. *Source: From Schott et al. (2004).*



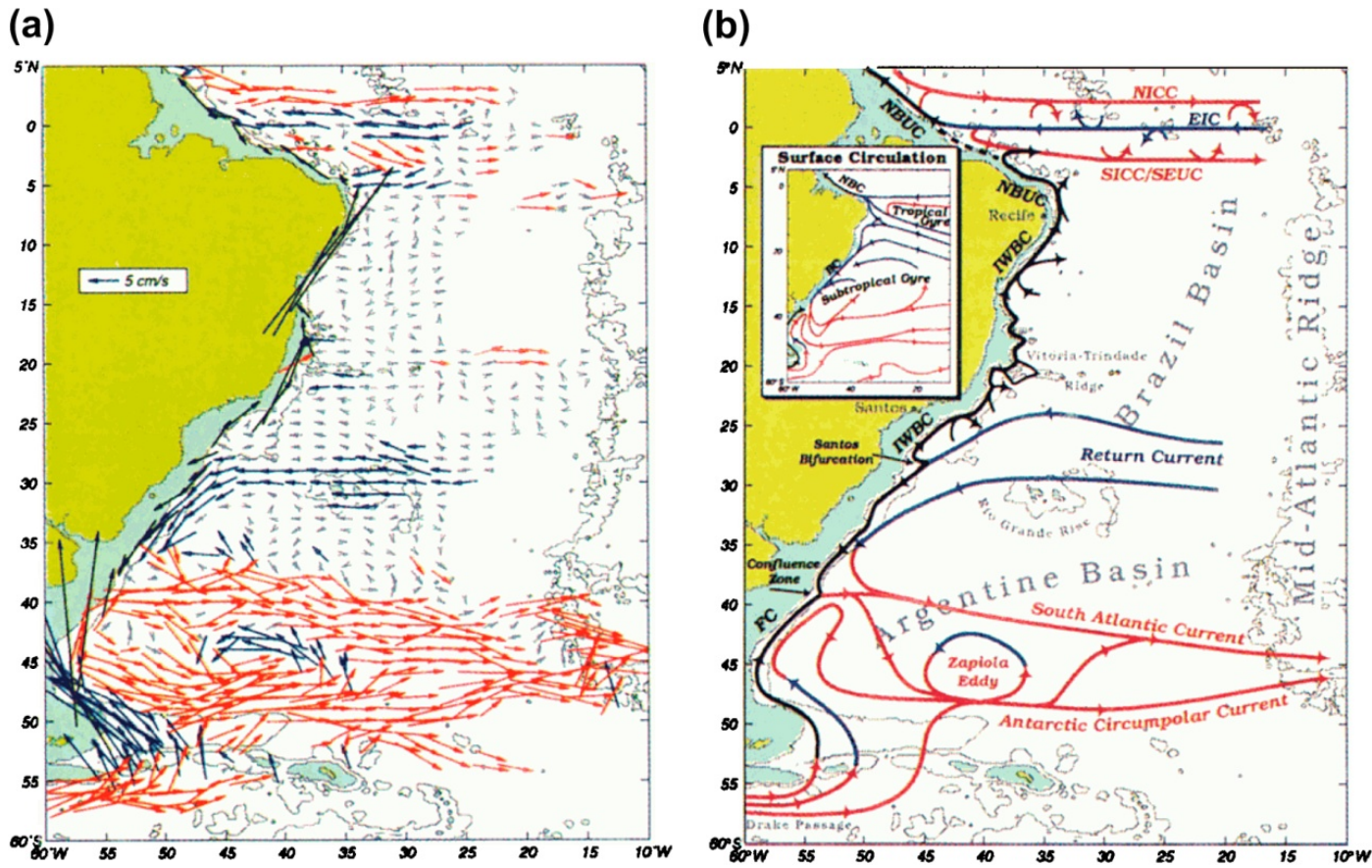
Gulf Stream velocity sections and transports. (a) Mean velocity of the Florida Current at the Straits of Florida at 27°N. Source: From *Leaman, Johns, and Rossby (1989)*. (b) Smoothed geostrophic velocity at Cape Hatteras. Source: From *Pickart and Smethie (1993)*. (c) Gulf Stream transport (Sv) at different longitudes; Cape Hatteras and the New England Seamounts are indicated by hatching. Barotropic and baroclinic transports are indicated. Source: From *Johns et al. (1995)*.

FIGURE 9.5



Subtropical North Atlantic at 24°N from July to August 1992. (a) Potential temperature (°C), (b) salinity, (c) oxygen ($\mu\text{mol}/\text{kg}$), and (d) CFC-11 (pmol/kg) at 24°N. This figure can be found in the color insert. (World Ocean Circulation Experiment section A05). Adapted: From *WOCE Atlantic Ocean Atlas; Jancke, Gouretski, and Koltermann (2011)*.

FIGURE 9.22



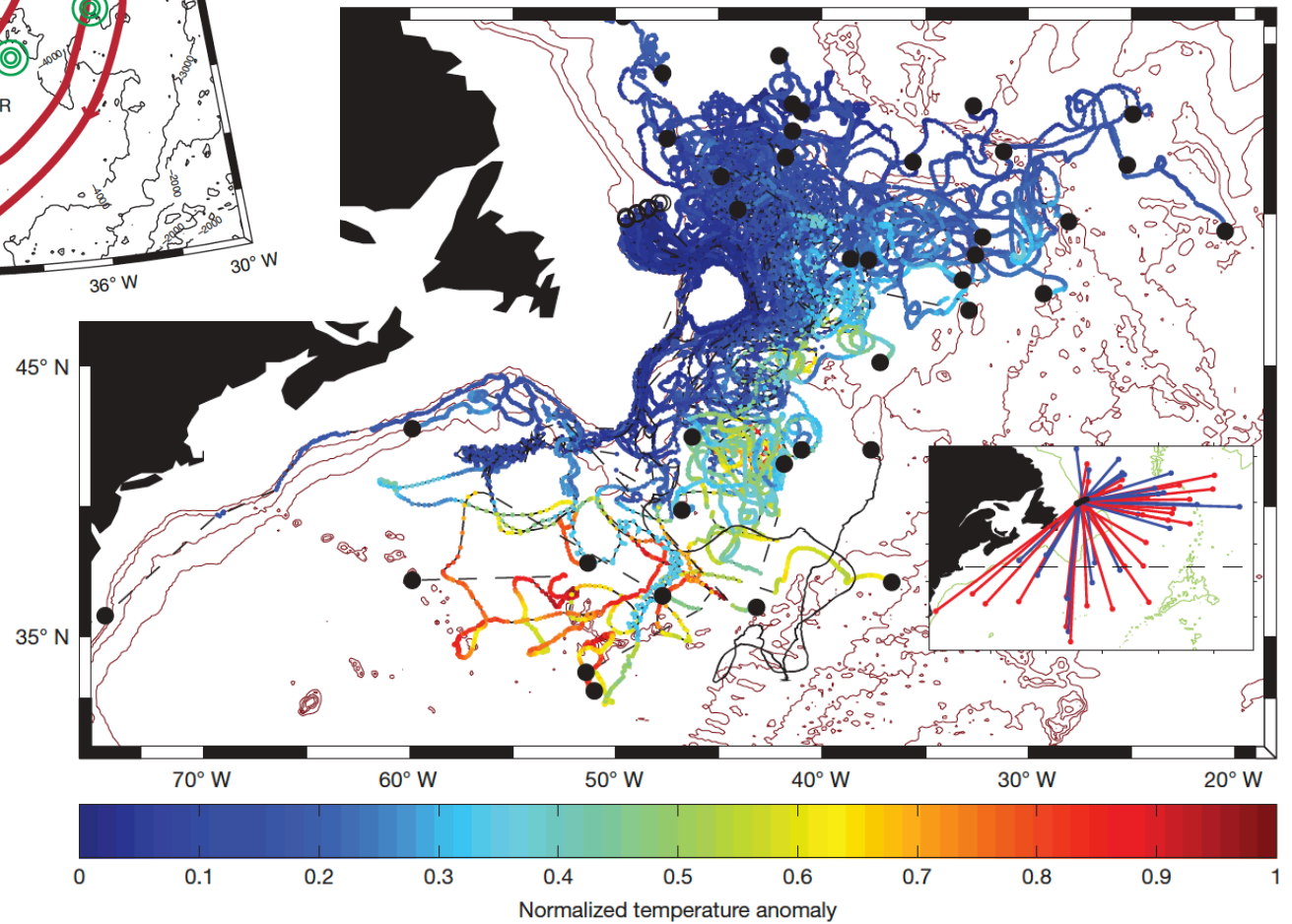
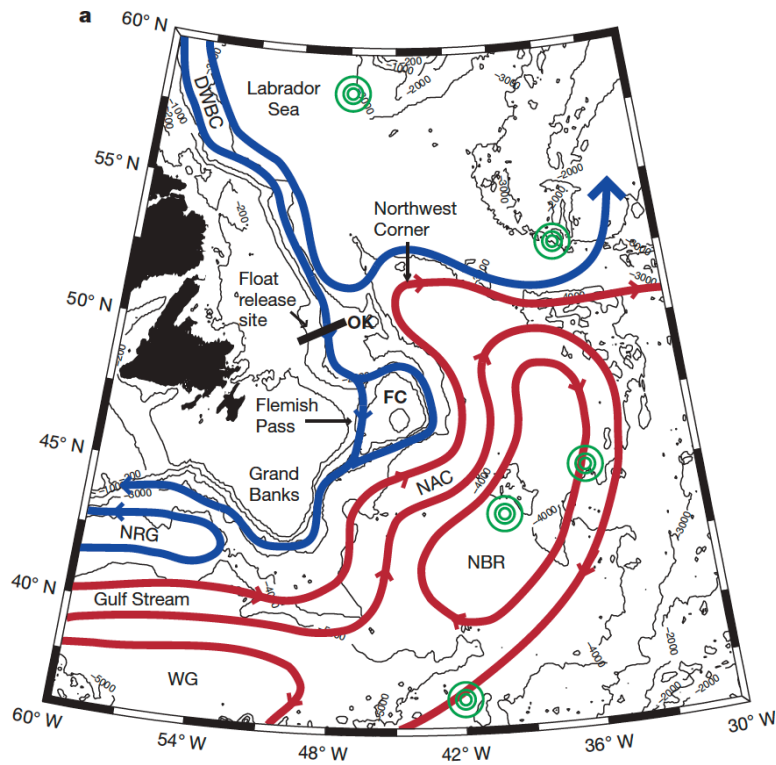
Deep Brazil and Malvinas Current structure. (a) Mean velocity and (b) circulation schematic at intermediate depth (650–1050 m) based on subsurface floats from different experiments during 1989–1996. *Source: From Boebel et al. (1999).*

FIGURE S9.17

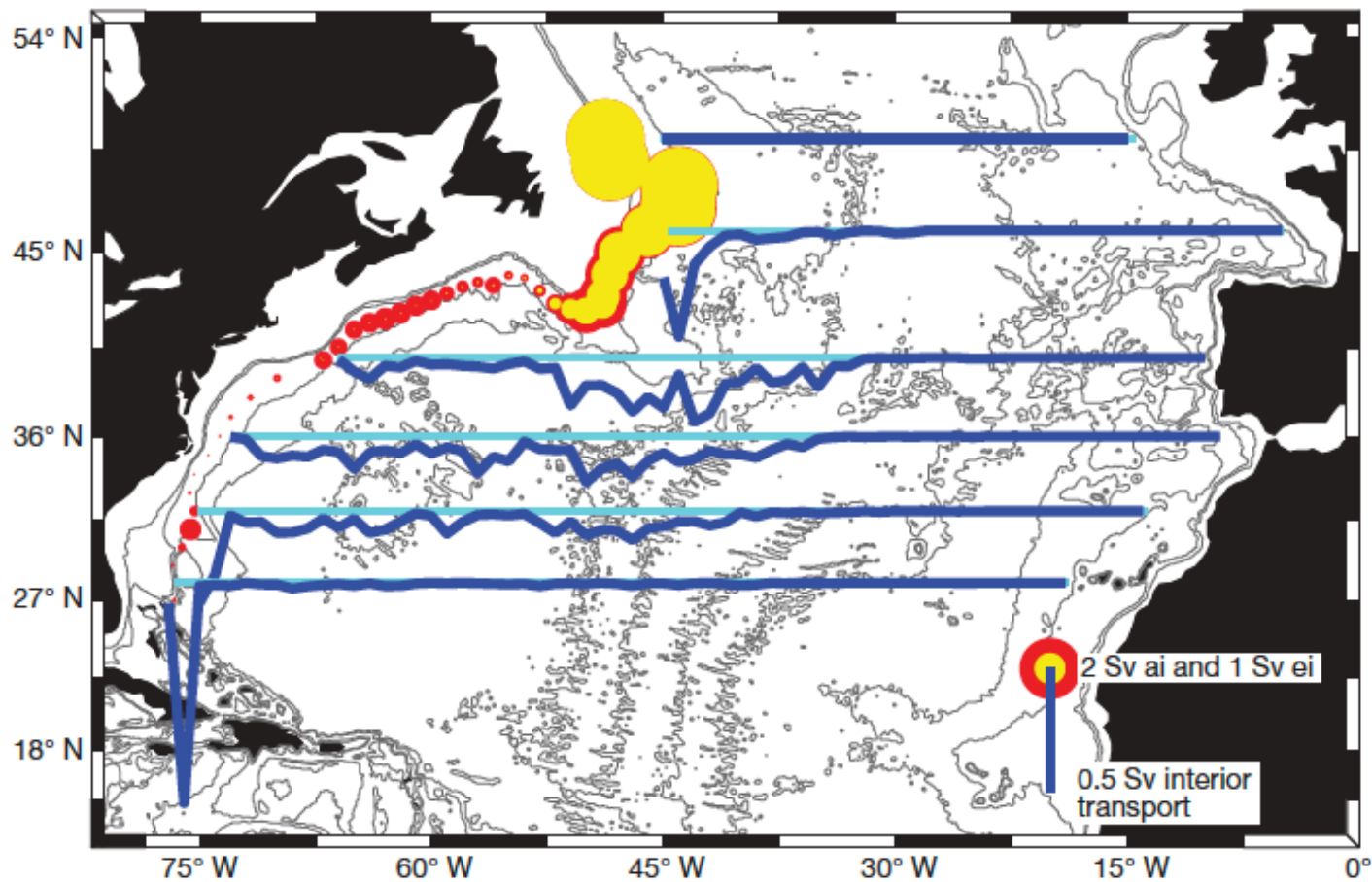
How coherent is the DWBC?

Bower et al. 2009

Observations – 2 year float trajectories



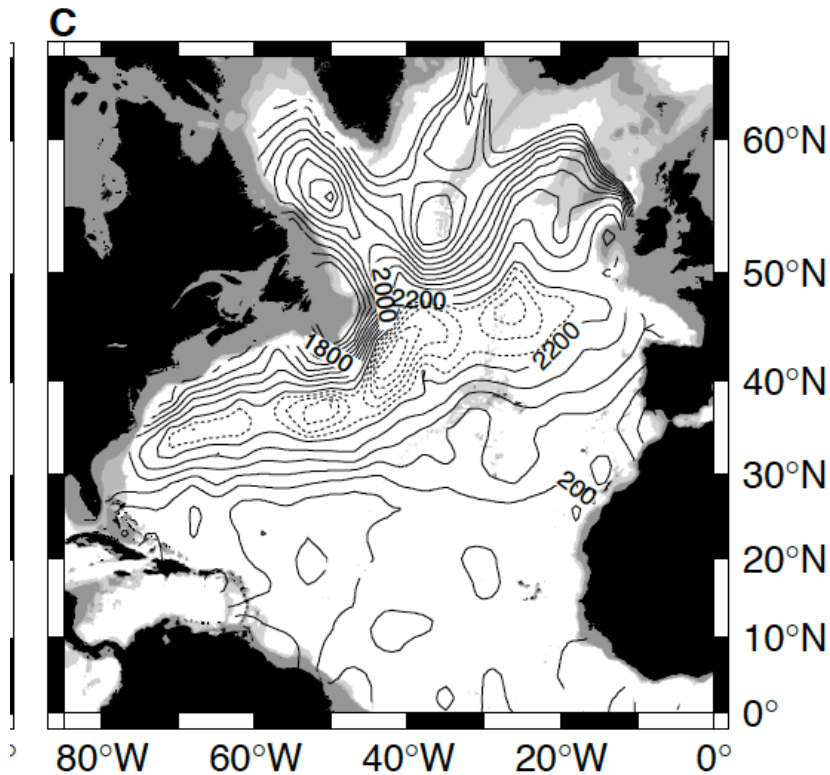
How much southward transport is in the DWBC vs. Interior?



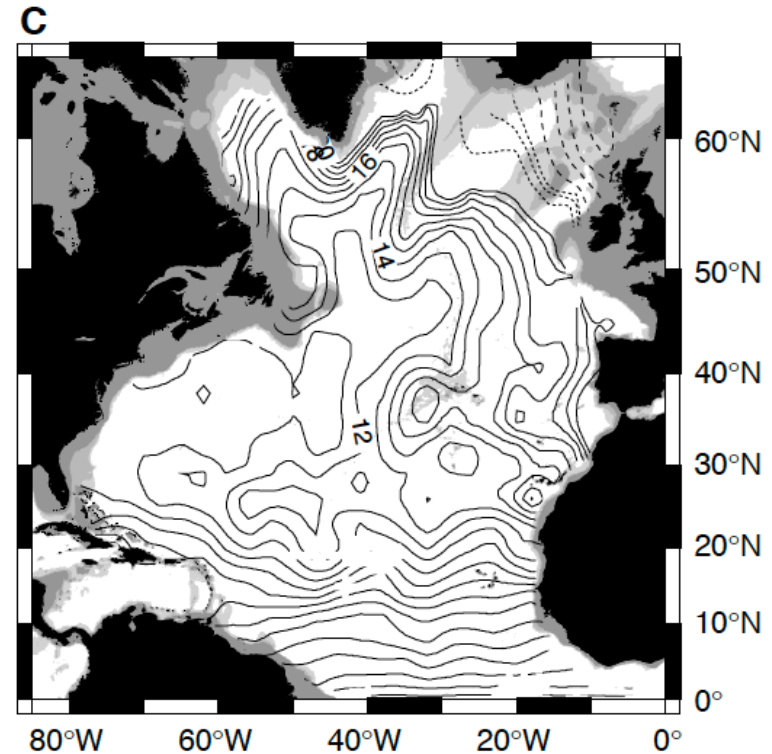
Closed pressure contours and homogenous PV indicates recirculation

Lozier 1997 – on $\sigma_2 = 36.95$ ($\sim 2000\text{m}$)

Pressure contours: geostrophic flow is
recirculating



PV (\sim conserved), also indicates
recirculation



Atlantic Summary

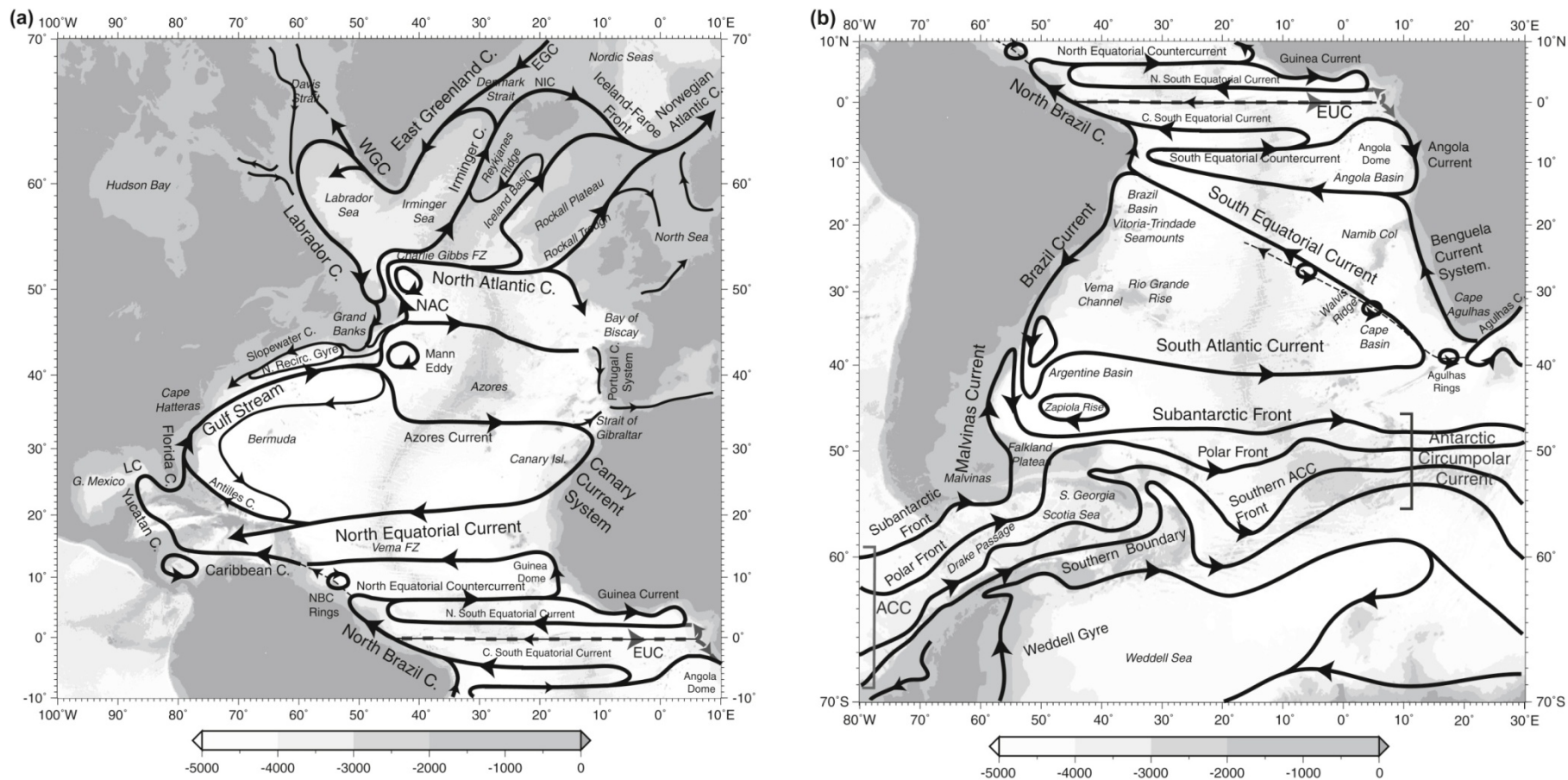
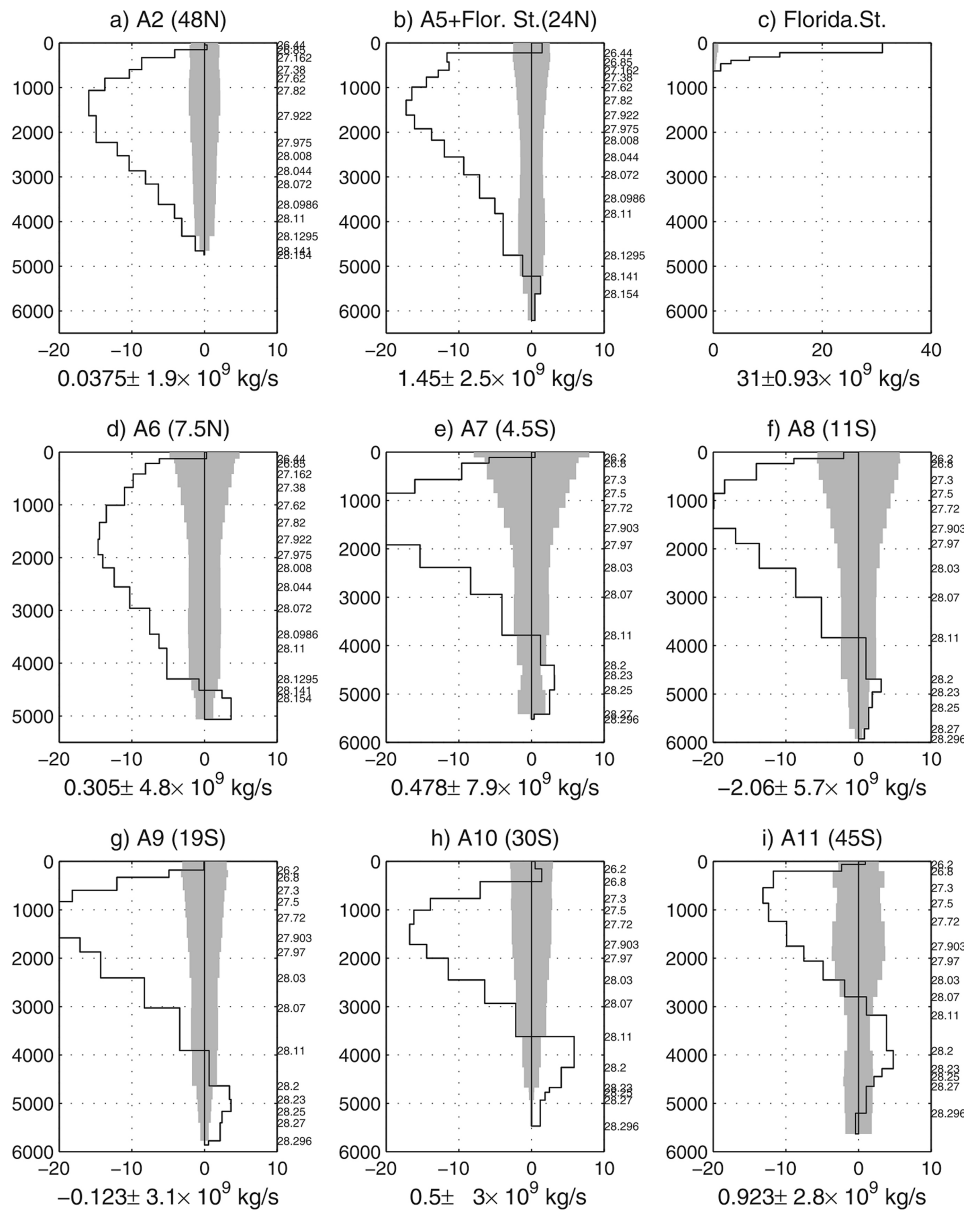


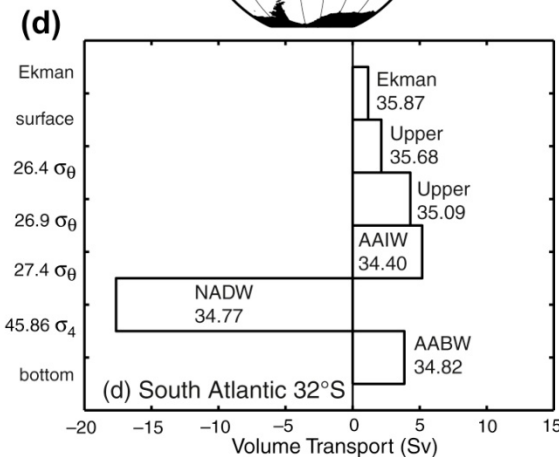
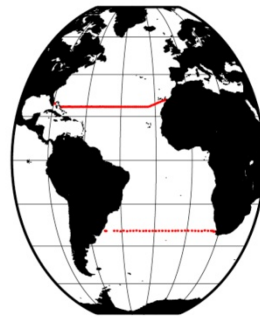
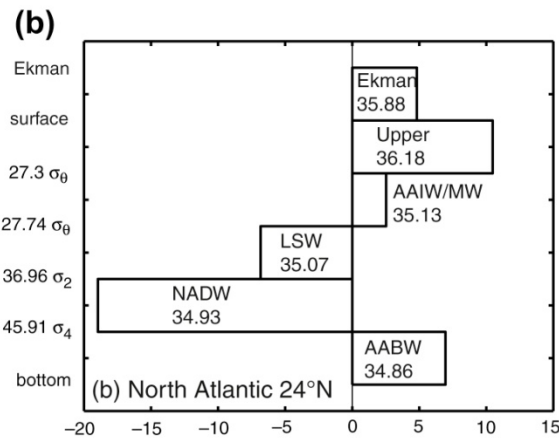
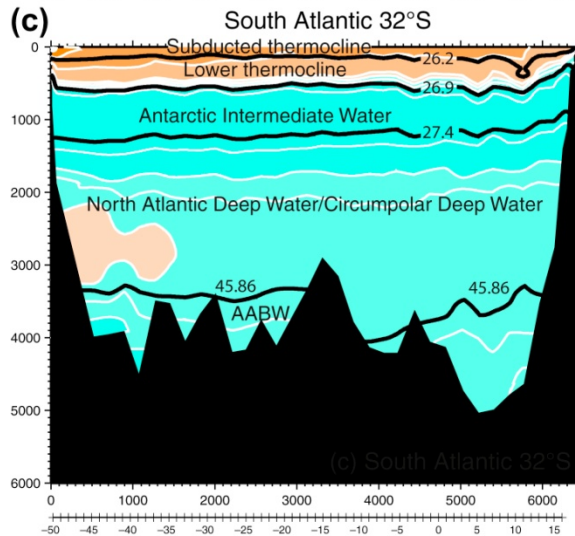
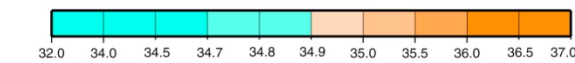
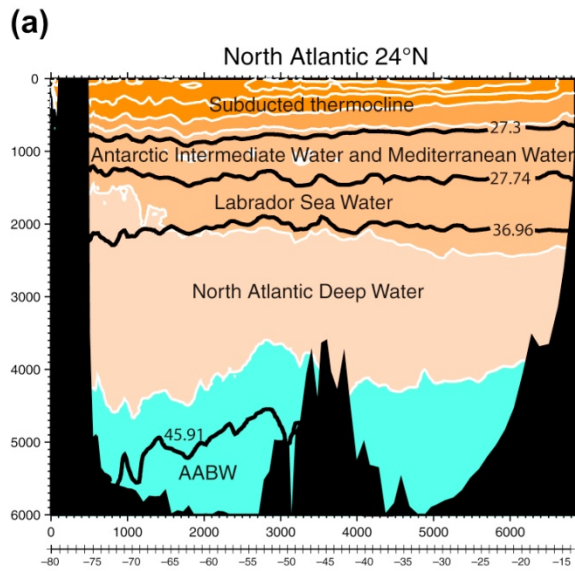
FIGURE 9.1

Atlantic Ocean surface circulation schematics. (a) North Atlantic and (b) South Atlantic; the eastward EUC along the equator just below the surface layer is also shown (gray dashed).



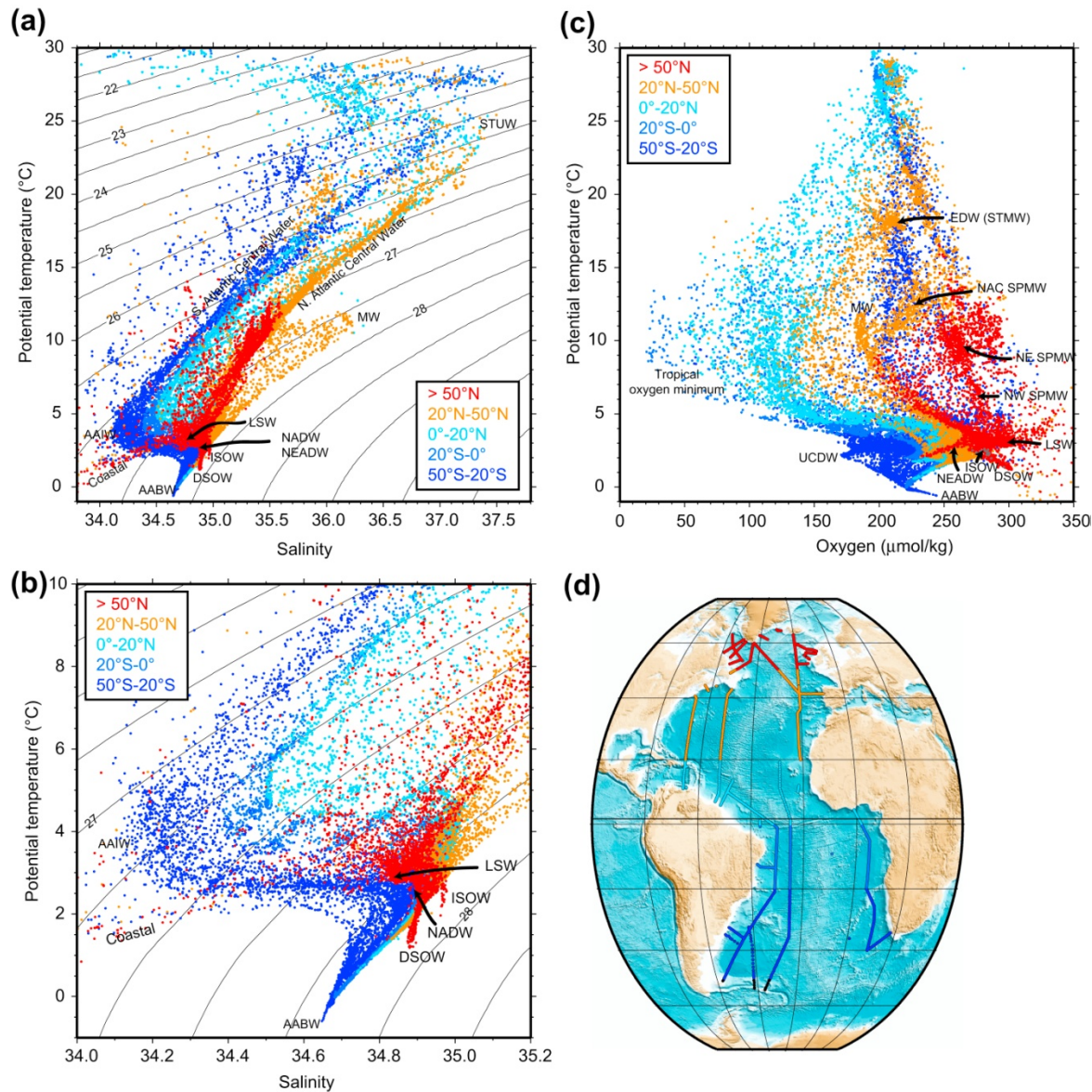
Northward transports (Sv) across zonal sections in isopycnal layers, integrated upward from zero at the bottom. Section latitudes are indicated in parentheses. Ekman transport is not included. Gray indicates the uncertainty. *Source: From Ganachaud (2003).*

FIGURE S9.25



Salinity and meridional transport in isopycnal layers at (a, b) 24°N in 1981 and (c, d) 32°S in 1959/1972. The inset map shows section locations. The isopycnals ($\sigma_\theta, \sigma_2, \sigma_4$) that define the layers are contoured in black on the salinity sections. Figures 9.16a, c can also be found in the color insert. See also online supplementary Figures S9.24 and S9.25 for examples from Bryden, Longworth, and Cunningham (2005b) and Ganachaud (2003). *After Talley (2008), based on Reid (1994) velocities.*

FIGURE 9.16



Potential temperature (°C) versus salinity for (a) full water column, and (b) water colder than 10°C. (c) Potential temperature versus oxygen for full water column. (d) Station location map. Colors indicate latitude range. Contours are potential density referenced to 0 dbar. Data are from the World Ocean Circulation Experiment (1988–1997). This figure can also be found in the color insert.

FIGURE 9.18

Southern Ocean

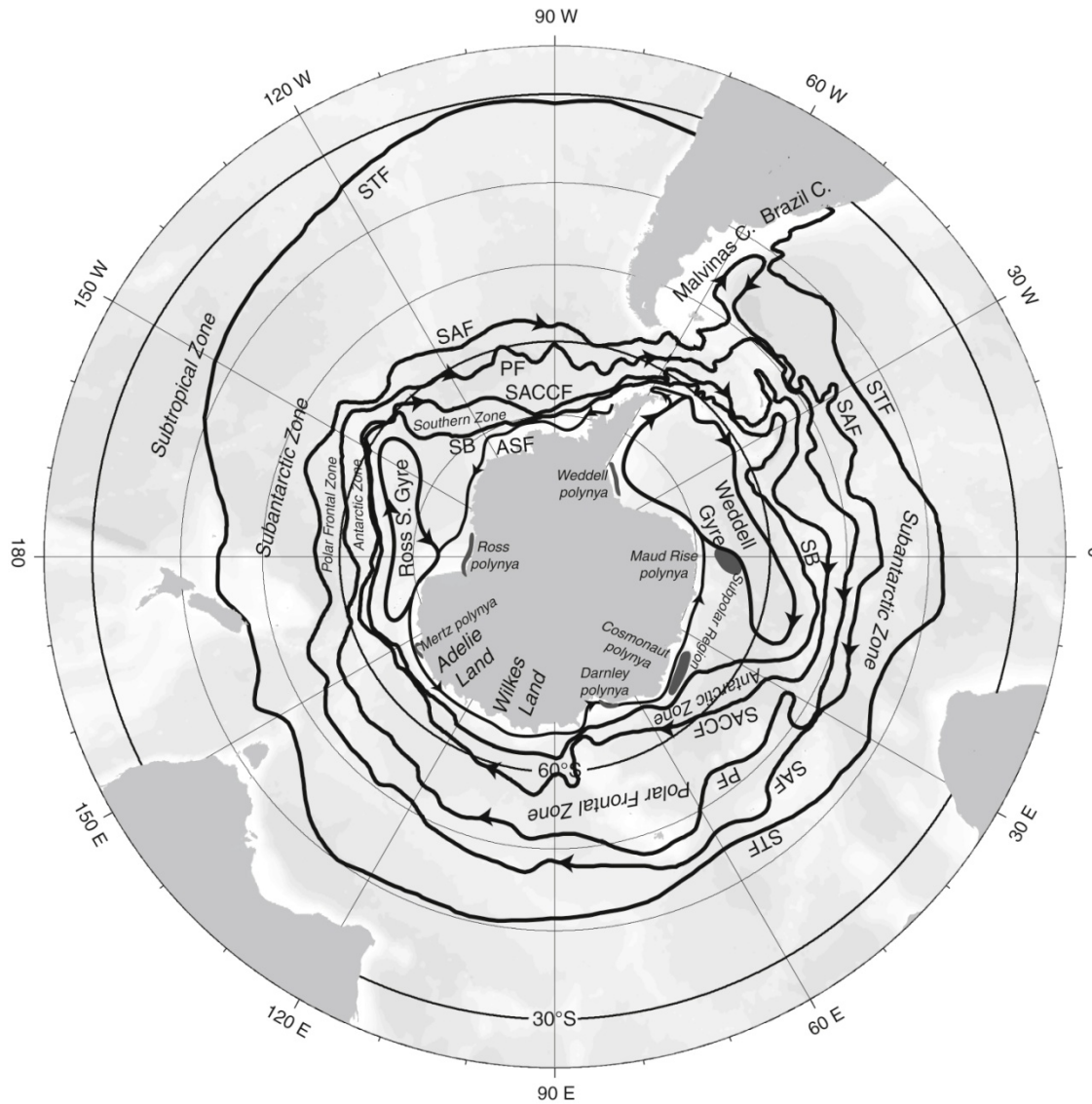
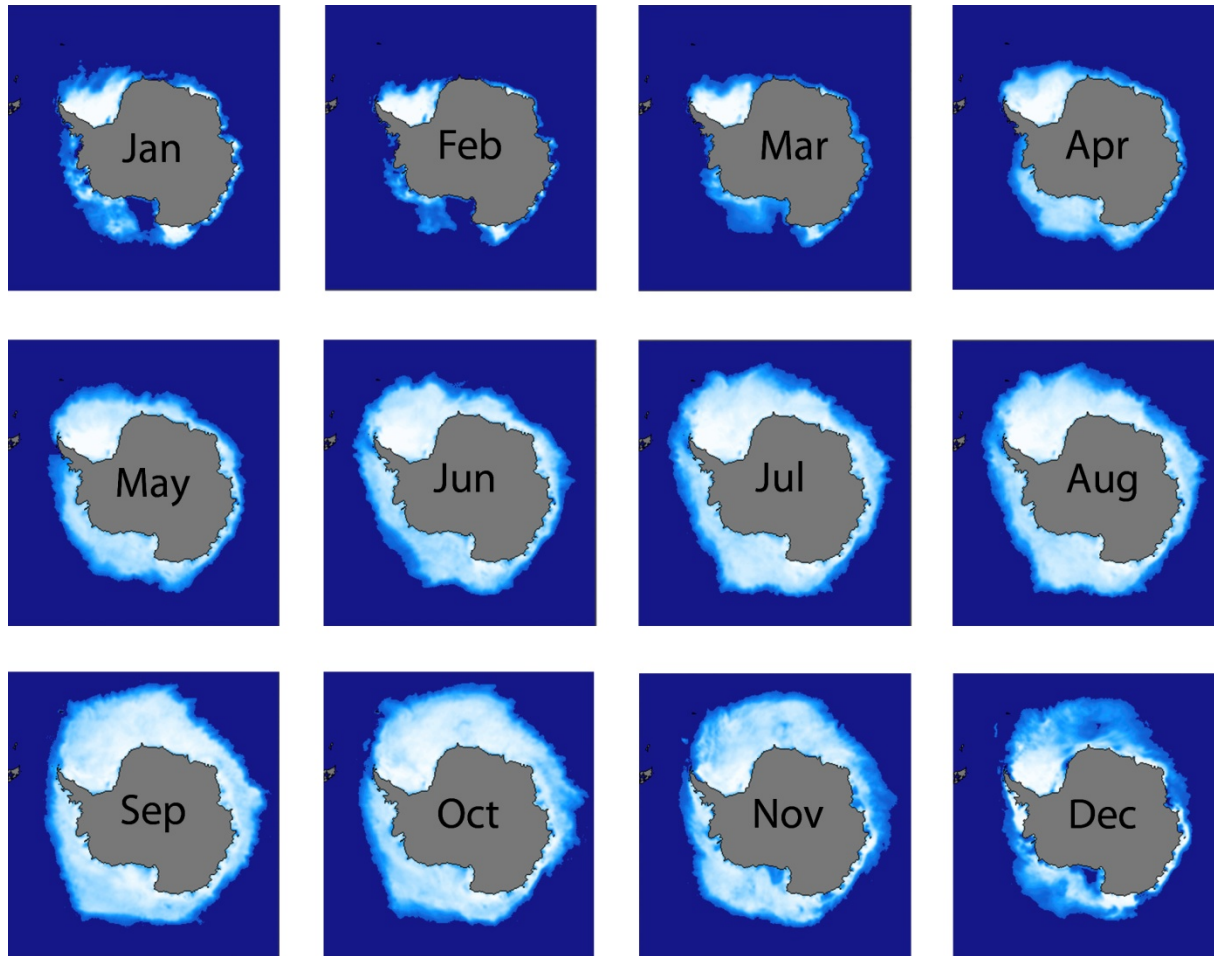


FIGURE 13.1

TALLEY

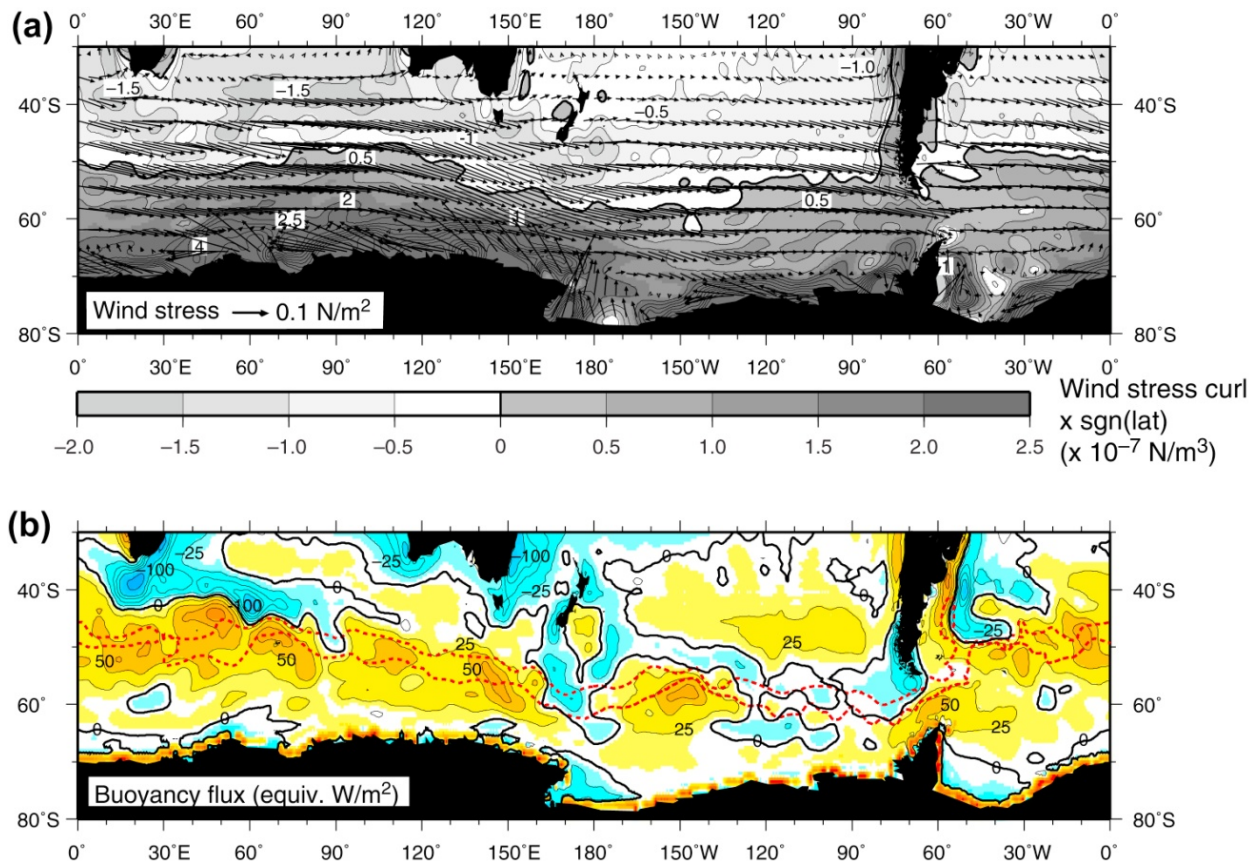
The Southern Ocean geography, principal fronts, and oceanographic zones (see Table 13.1). The Subtropical Front (STF) is the oceanographic northern boundary for the region. The eastward Antarctic Circumpolar Current (ACC) includes these fronts: Subantarctic Front (SAF), Polar Front (PF), Southern ACC Front (SACCF), Southern Boundary (SB). Front locations from Orsi et al. (1995). The westward Antarctic Slope Front (ASF) (thin) follows the continental slope. Circulation of the ocean basins north of the SAF is not represented; see the maps in Chapters 9, 10 and 11. Major polynyas (dark gray patches) are labeled; all polynyas are shown in Figure 13.20.

Copyright © 2011 Elsevier Inc. All rights reserved



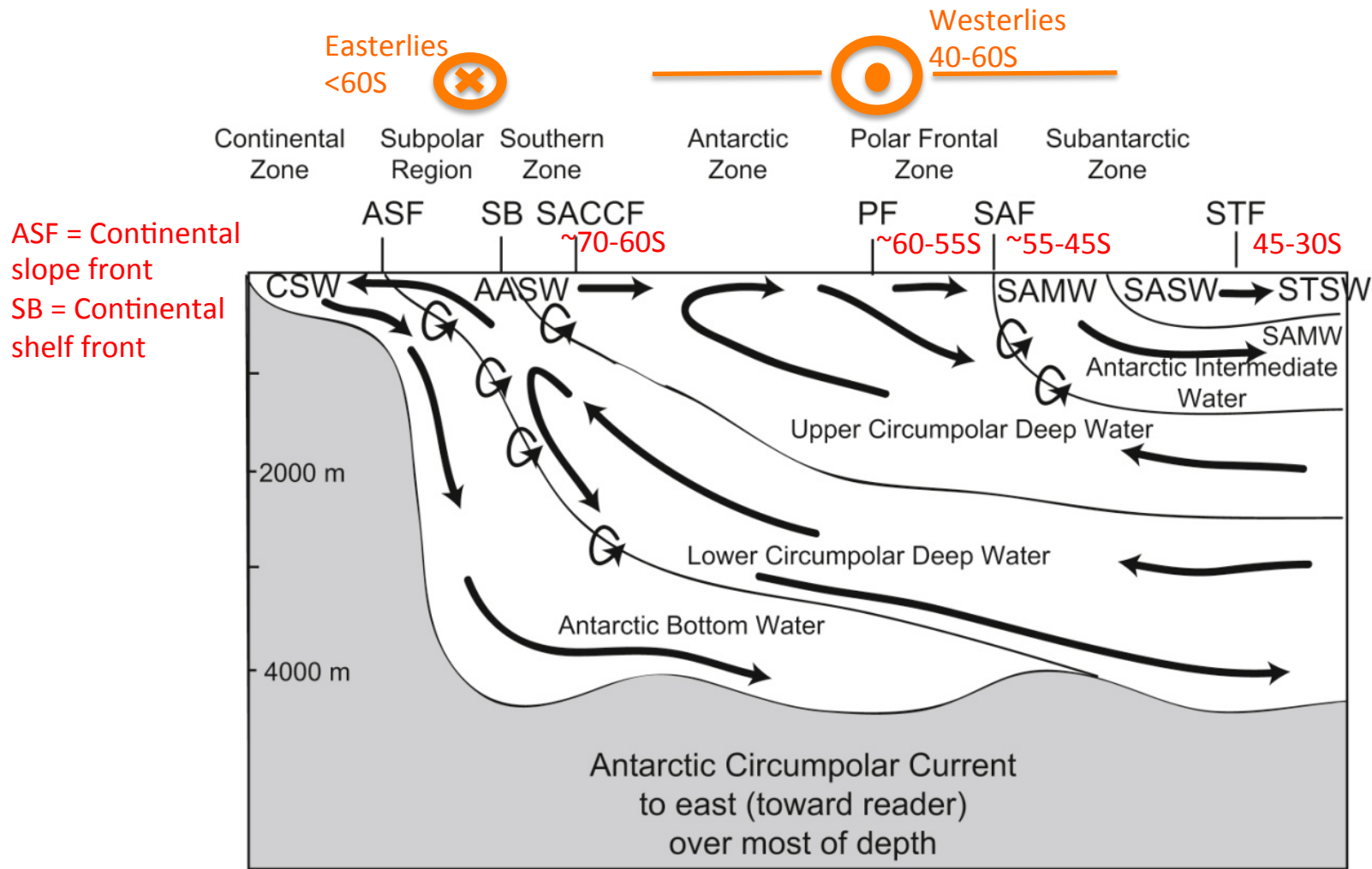
Annual progression of sea ice concentration in 1991, computed from the Special Sensor Microwave Imager (SSM/I) carried on the Defense Meteorological Satellite Program satellites. *Source: From Cavalieri, Parkinson, Gloersen, and Zwally (1996, 2008).*

FIGURE 13.19



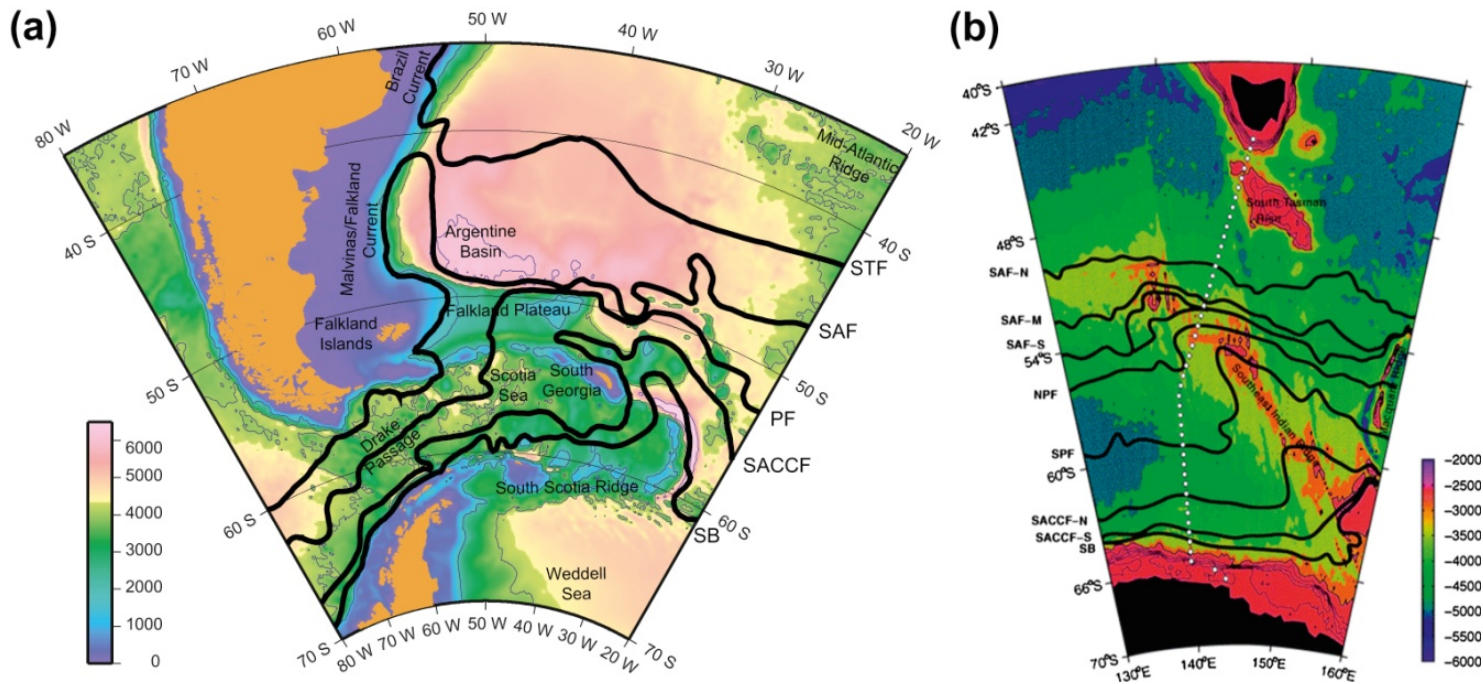
(a) Annual average wind stress (N/m^2) (vectors) and wind stress curl ($\times 10^{-7} \text{ N}/\text{m}^3$) (shading) multiplied by -1 in the Southern Hemisphere so that positive values (dark grays) indicate Ekman upwelling, from the NCEP reanalysis 1968-1996 (Kalnay et al., 1996). (b) Annual mean air-sea buoyancy flux, converted to equivalent heat flux (W/m^2), based on Large and Yeager (2009) air-sea fluxes. Positive values indicate that the ocean is becoming less dense. Contour interval is $25 \text{ W}/\text{m}^2$ (grid-scale contouring along the Antarctic coast has been removed). Dashed contours are the Subantarctic and Polar Fronts from Orsi et al. (1995).

FIGURE 13.2



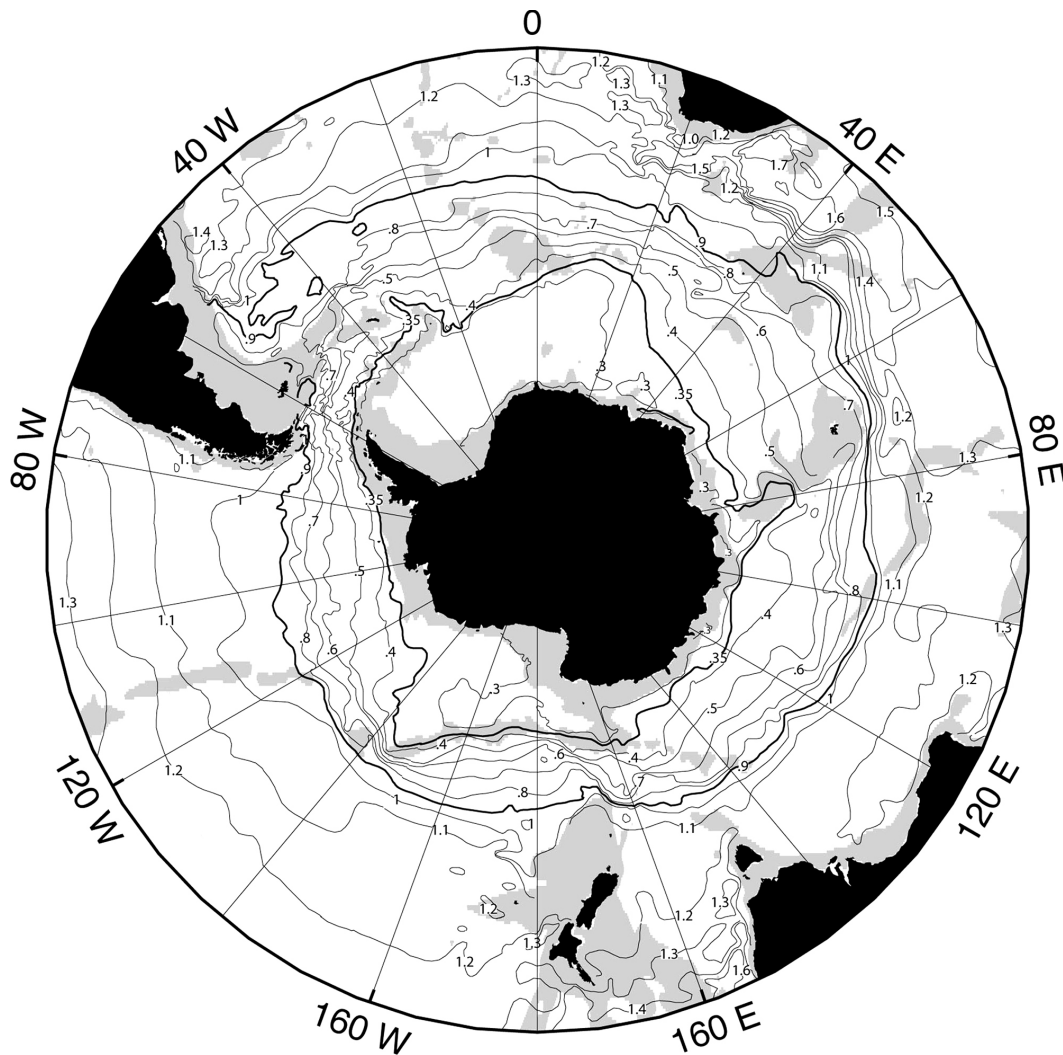
A schematic meridional section in the Southern Ocean showing the water masses, meridional circulation, fronts, and most zones. Acronyms: Continental Shelf Water (CSW), Antarctic Surface Water (AASW), Subantarctic Mode Water (SAMW), Subantarctic Surface Water (SASW), Subtropical Surface Water (STSW), Antarctic Slope Front (ASF), Southern Boundary (SB), Southern ACC Front (SACCF), Polar Front (PF), Subantarctic Front (SAF), and Subtropical Front (STF). *After Speer, Rintoul, and Sloyan (2000).*

FIGURE 13.4



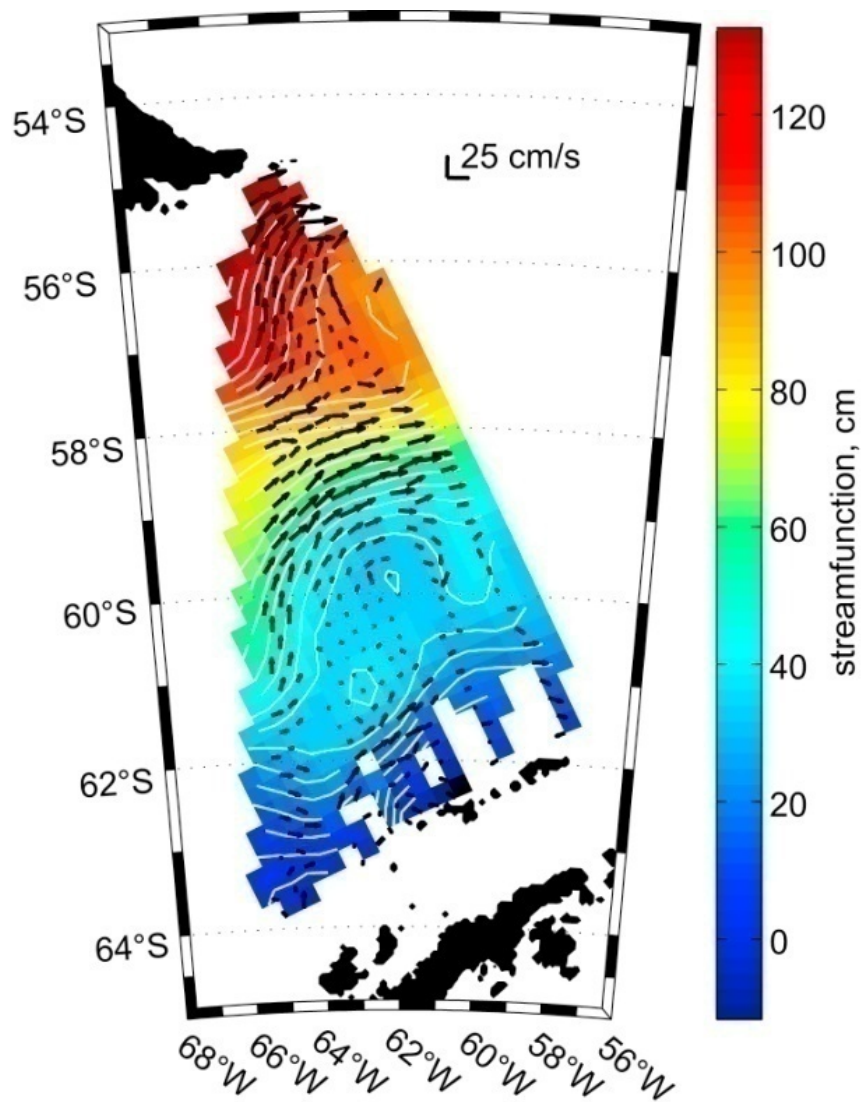
(a) Drake Passage and southwest Atlantic fronts. (*Fronts from Orsi et al., 1995; bathymetry (m) from Smith & Sandwell, 1997.*) (b) Fronts south of Australia (Tasmania). N, M, and S refer to northern, middle, and southern branches of the given fronts. *Source: From Sokolov and Rintoul (2002).*

FIGURE 13.5



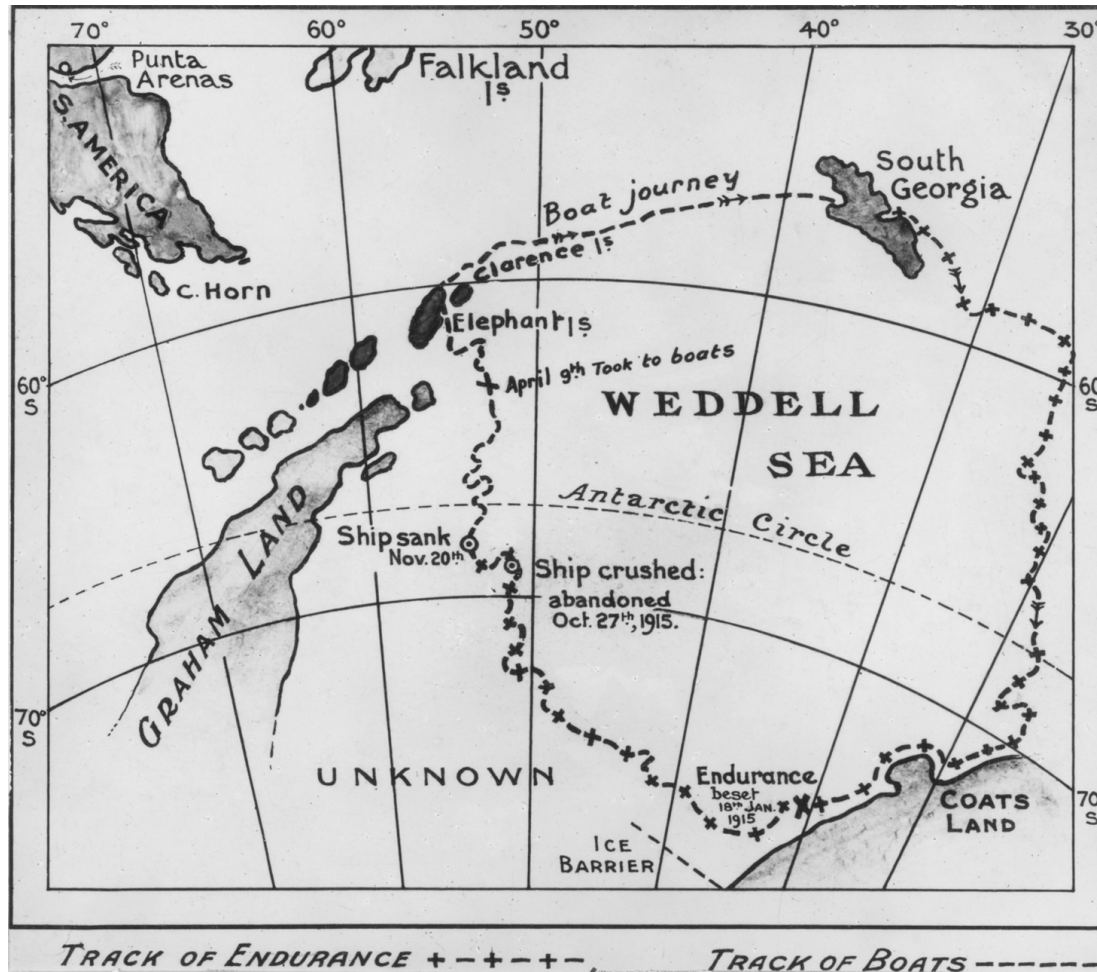
Geopotential height anomaly at 50 dbar relative to 1000 dbar, in dynamic meters (10 J kg^{-1}). *Source: From Orsi et al. (1995).*

FIGURE 13.8



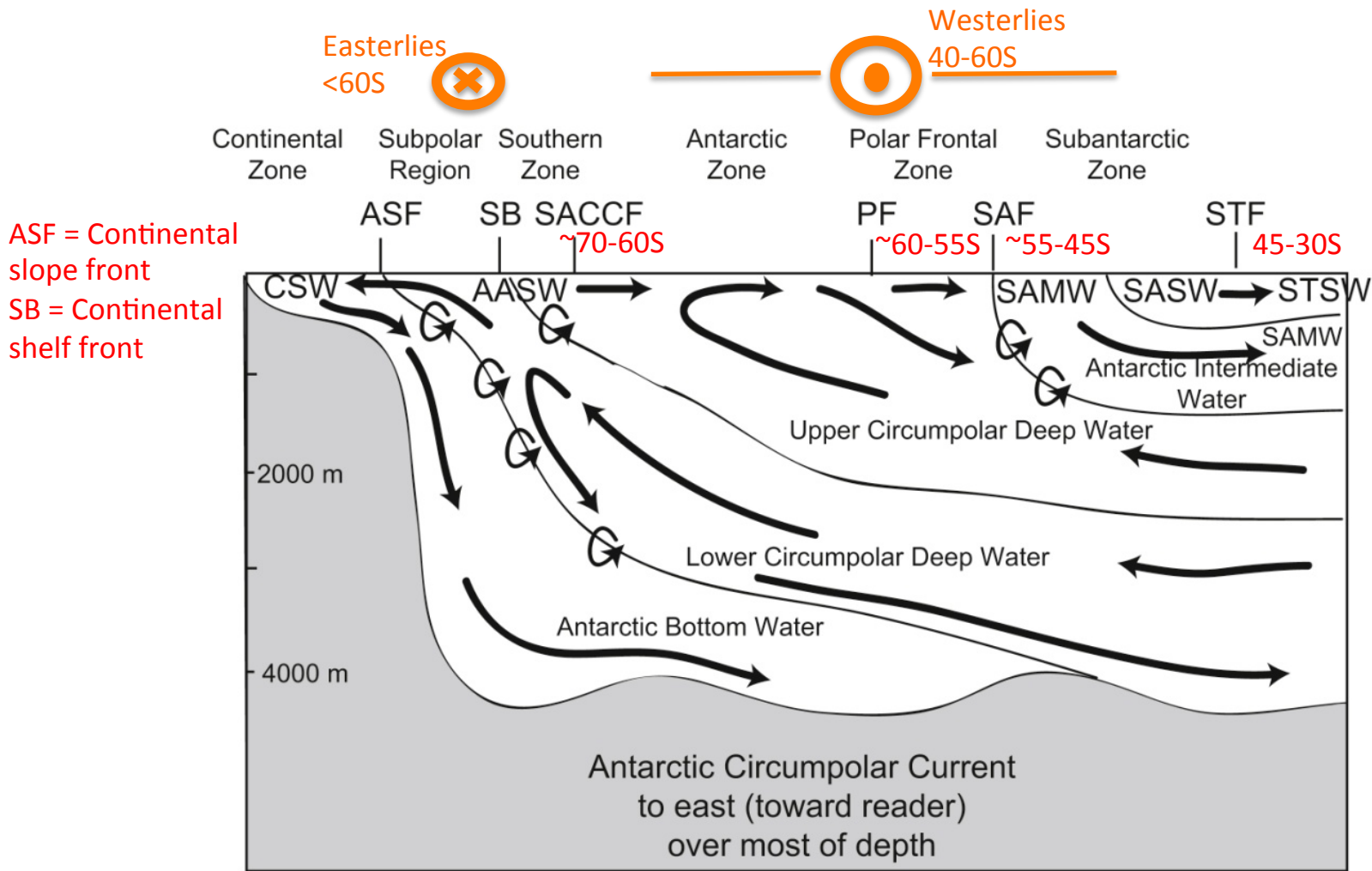
Mean currents in the Drake Passage, averaged over 30-300 m depth, from 128 ADCP crossings over 5 years. Strong currents from north to south are the Subantarctic Front (56°S), the Polar Front (59°S), and the Southern ACC Front (62°S). This figure can also be found in the color insert. *After Lenn, Chereskin, and Sprintall (2008).*

FIGURE 13.9



Track of the Endurance (1914-1916). Source: From Stone (1914); © Royal Geographical Society.

FIGURE 13.10



A schematic meridional section in the Southern Ocean showing the water masses, meridional circulation, fronts, and most zones. Acronyms: Continental Shelf Water (CSW), Antarctic Surface Water (AASW), Subantarctic Mode Water (SAMW), Subantarctic Surface Water (SASW), Subtropical Surface Water (STSW), Antarctic Slope Front (ASF), Southern Boundary (SB), Southern ACC Front (SACCF), Polar Front (PF), Subantarctic Front (SAF), and Subtropical Front (STF). *After Speer, Rintoul, and Sloyan (2000).*

FIGURE 13.4

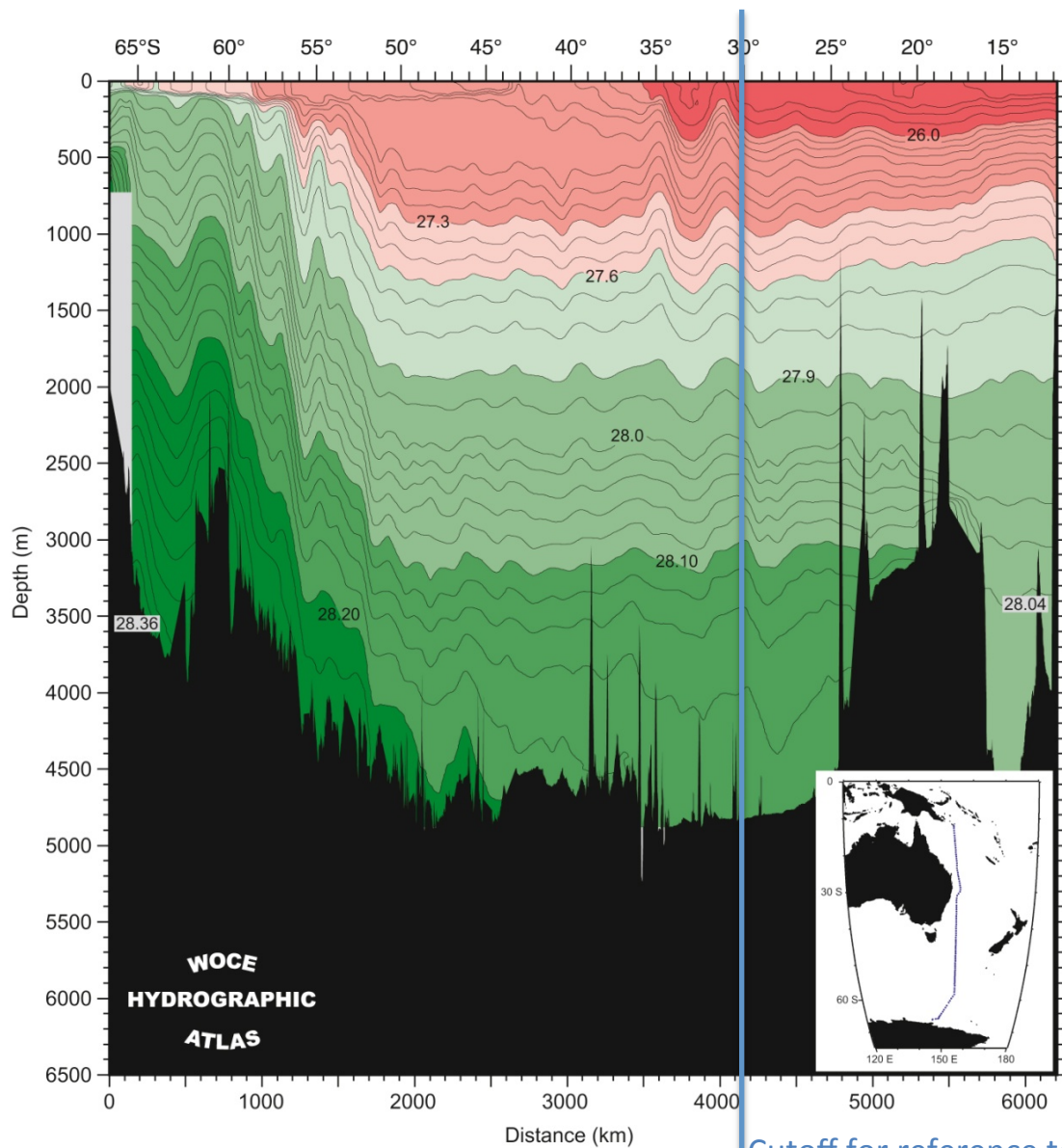
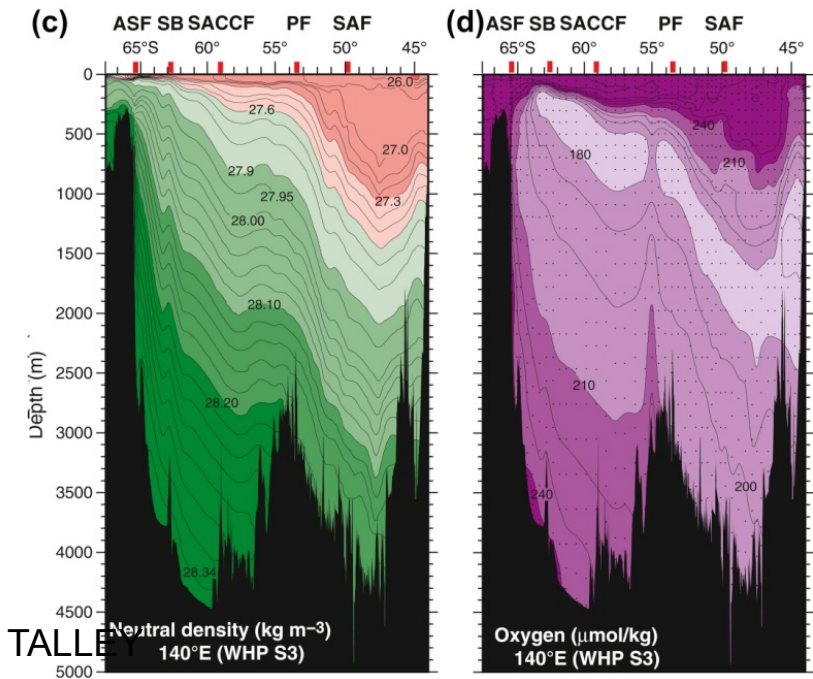
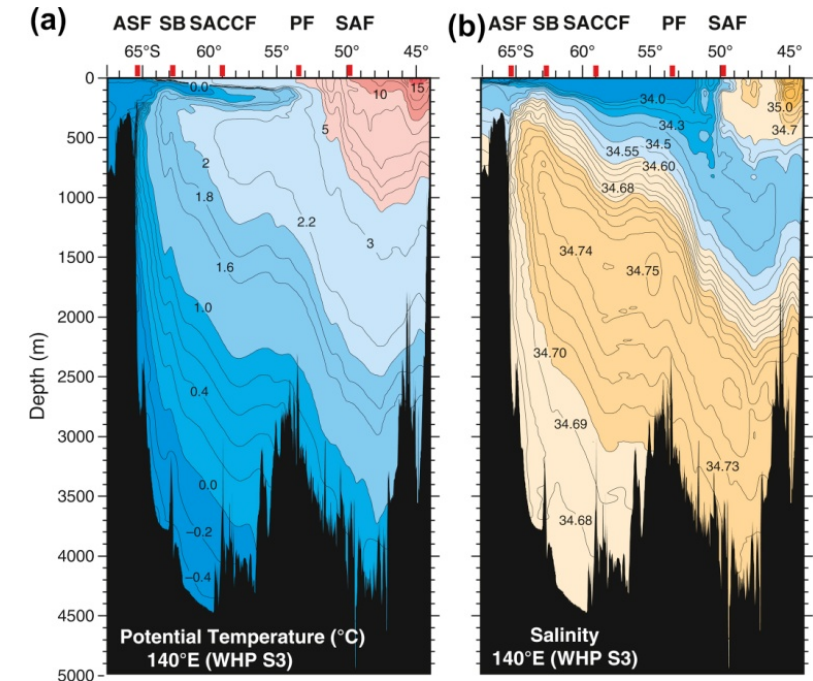


FIGURE 13.12

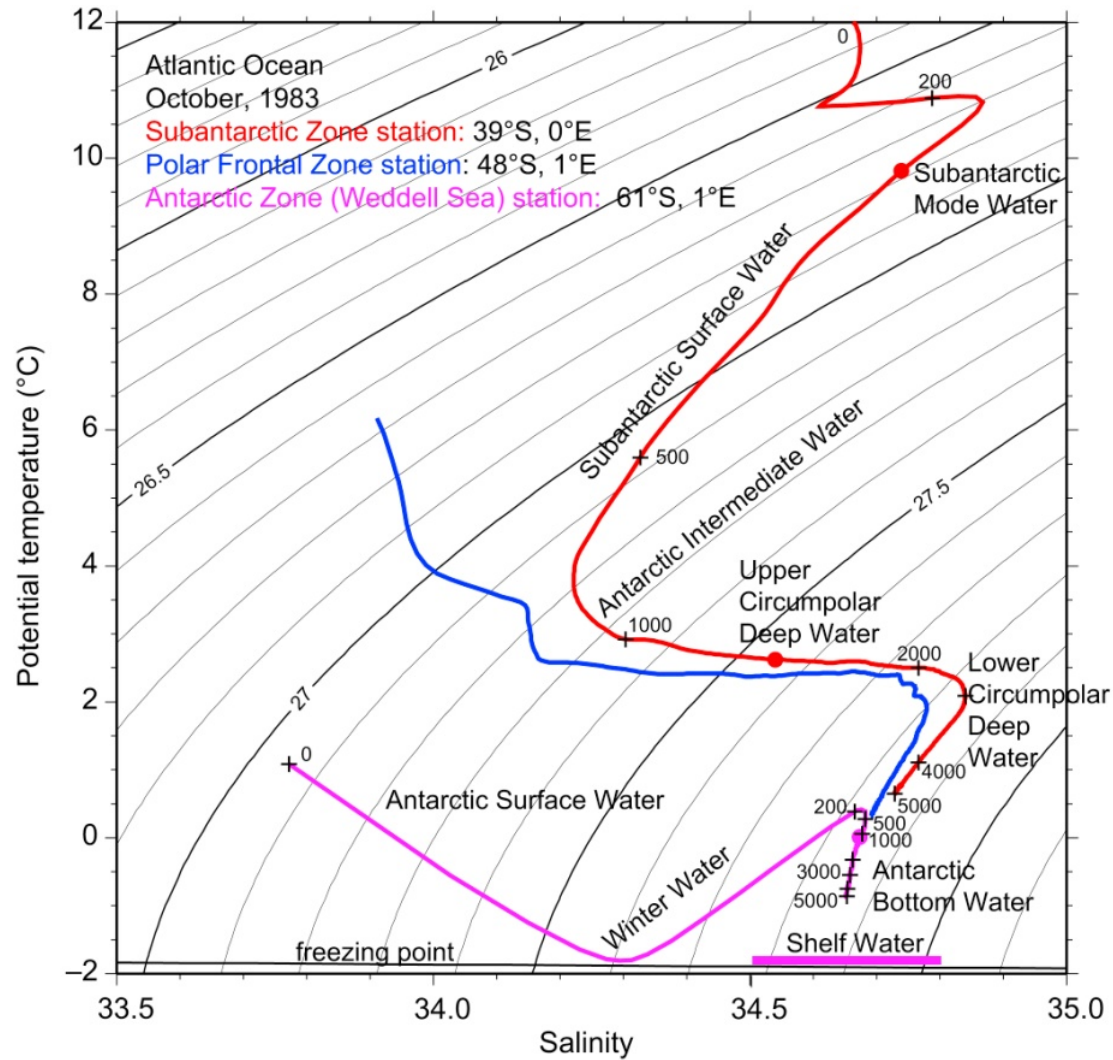
Cutoff for reference to
schematic Figure 13.4

Neutral density section in the western Pacific into the Tasman Sea (WOCE section P11, location on insert). *Source: From WOCE Pacific Ocean Atlas, Talley (2007).*



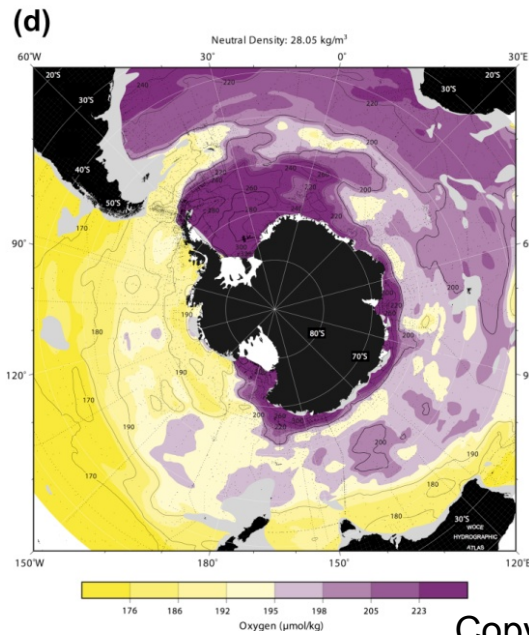
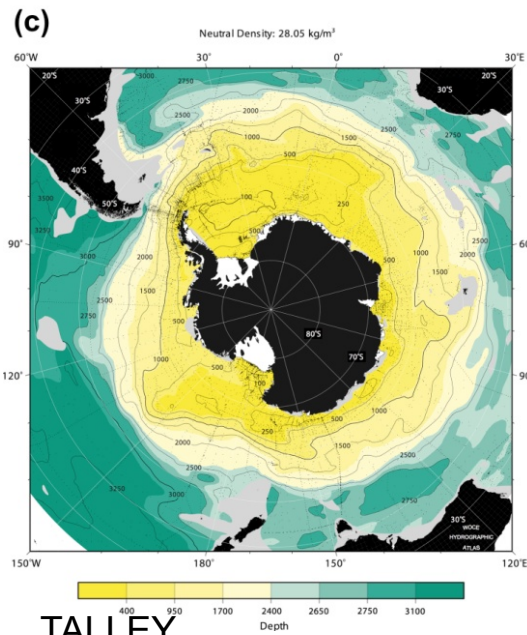
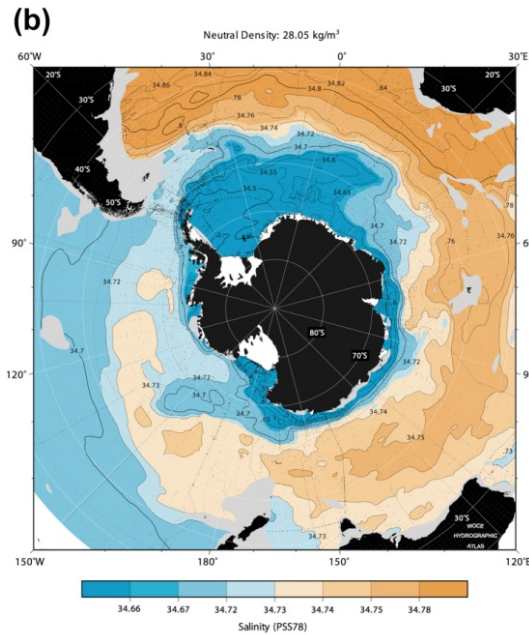
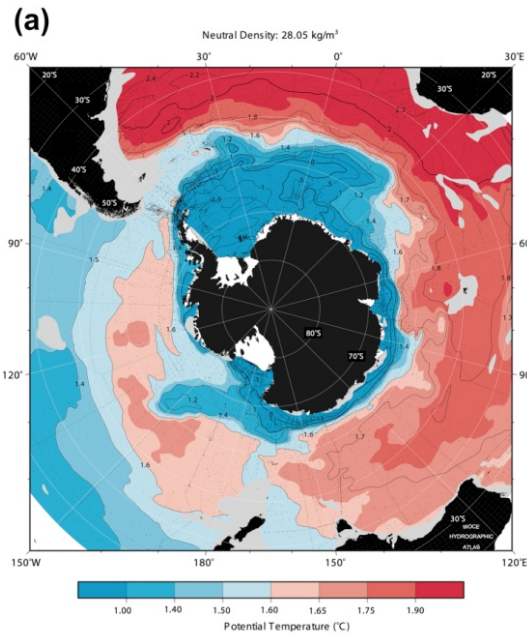
(a) Potential temperature (°C), (b) salinity, (c) neutral density (kg m⁻³), and (d) oxygen (μmol/kg) along 140°E from Antarctica to Tasmania (WOCE Hydrographic Programme Atlas section S3, from Talley, 2007). Fronts: Subantarctic Front (SAF), Polar Front (PF), Southern ACC Front (SACCF), Southern Boundary (SB), and Antarctic Slope Front (ASF). Location of section is shown by station dots in Figure 13.5b.

FIGURE 13.6



Potential temperature-salinity curve of Southern Ocean waters in the Atlantic sector showing the different water masses.

FIGURE 13.13

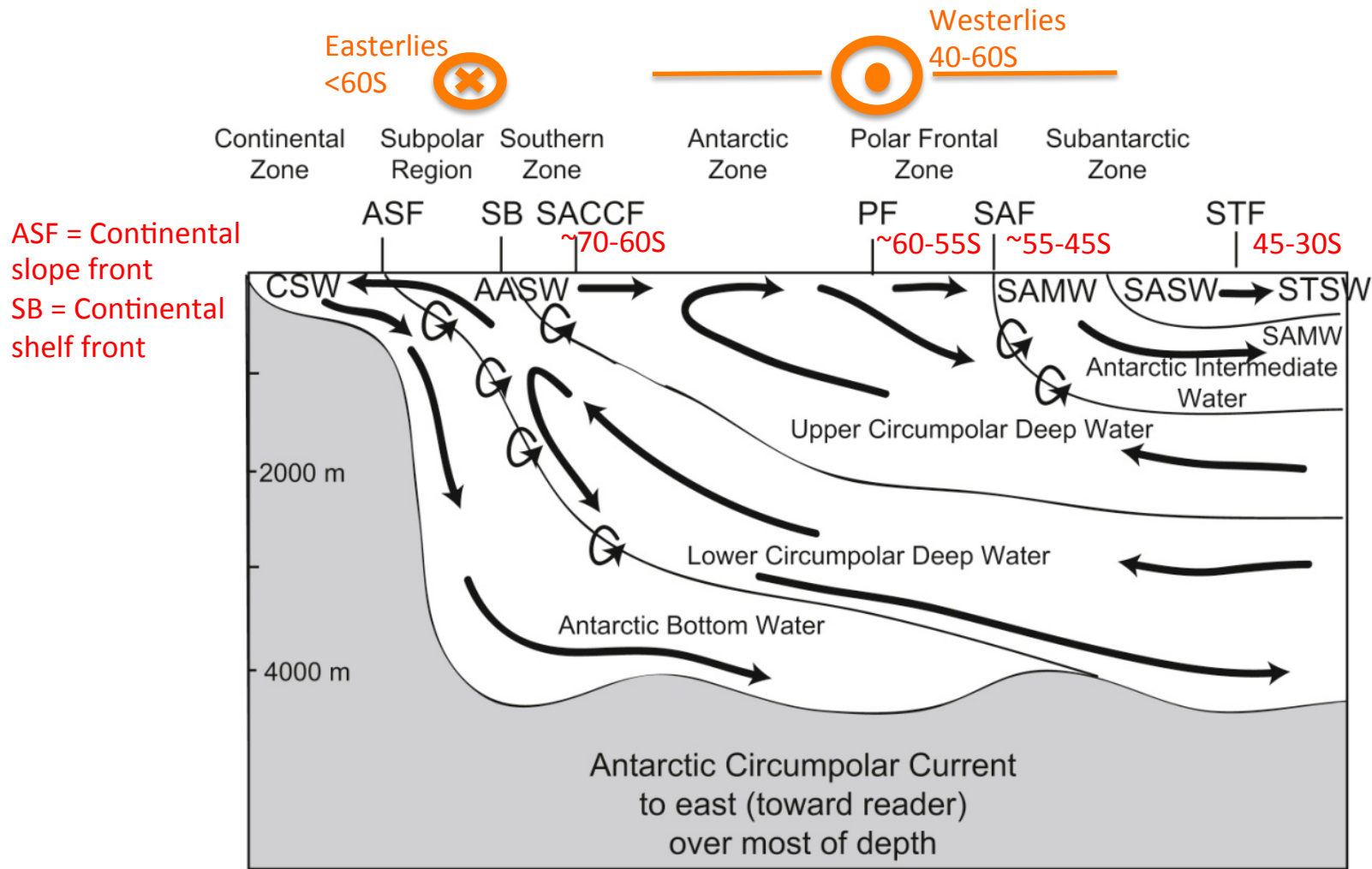


Properties along a Lower Circumpolar Deep Water isopycnal (neutral density 28.05 kg m⁻³), corresponding roughly to the salinity maximum core. (a) Potential temperature (°C), (b) salinity, (c) depth (m), (d) oxygen (μmol/kg). This figure can also be found in the color insert. Source: From WOCE Southern Ocean Atlas, Orsi and Whitworth (2005).

FIGURE 13.15

TALLEY

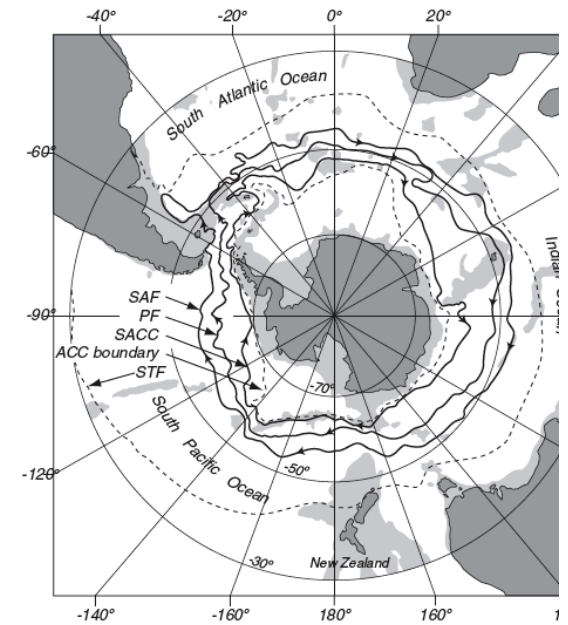
Copyright © 2011 Elsevier Inc. All rights reserved



A schematic meridional section in the Southern Ocean showing the water masses, meridional circulation, fronts, and most zones. Acronyms: Continental Shelf Water (CSW), Antarctic Surface Water (AASW), Subantarctic Mode Water (SAMW), Subantarctic Surface Water (SASW), Subtropical Surface Water (STSW), Antarctic Slope Front (ASF), Southern Boundary (SB), Southern ACC Front (SACCF), Polar Front (PF), Subantarctic Front (SAF), and Subtropical Front (STF). After Speer, Rintoul, and Sloyan (2000).

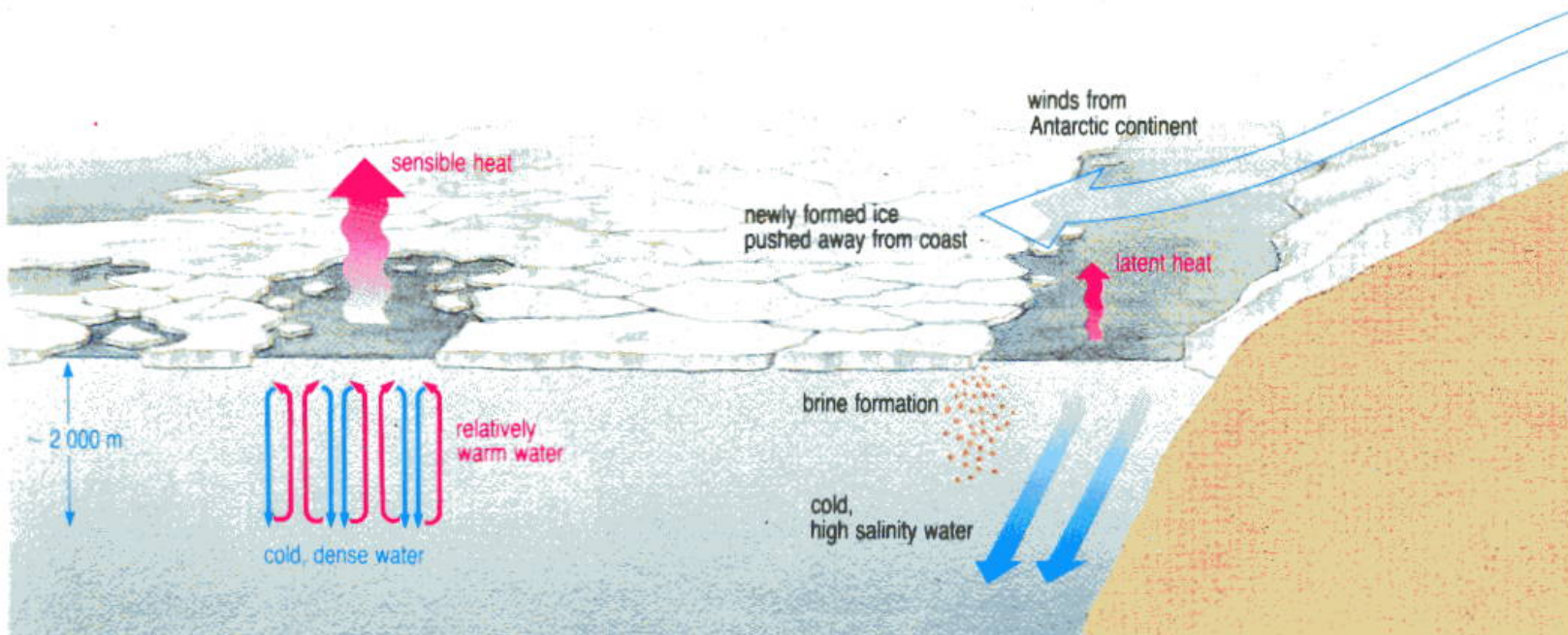
FIGURE 13.4

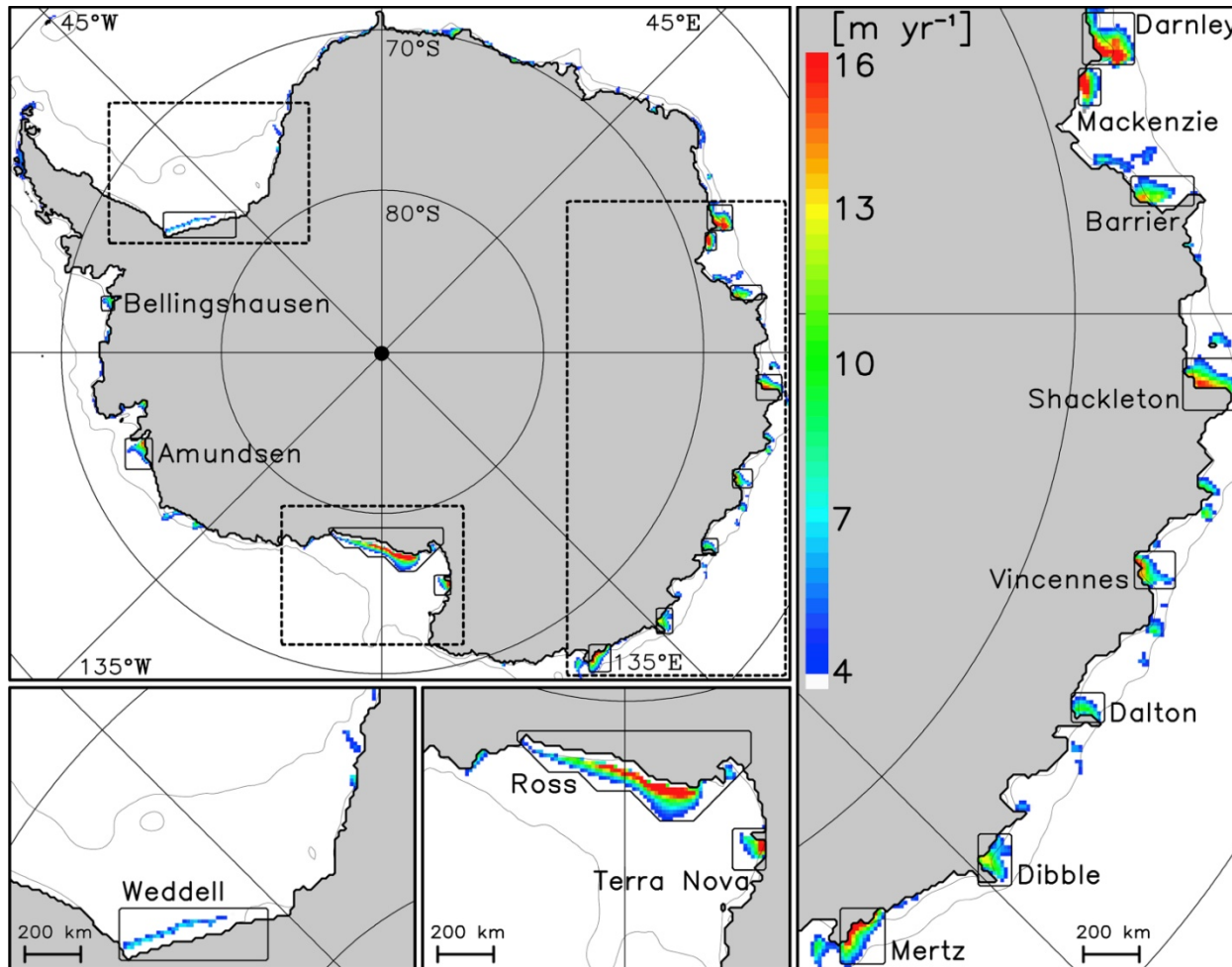
Polynyna – Sea Ice “factory”



'OPEN OCEAN' POLYNYA

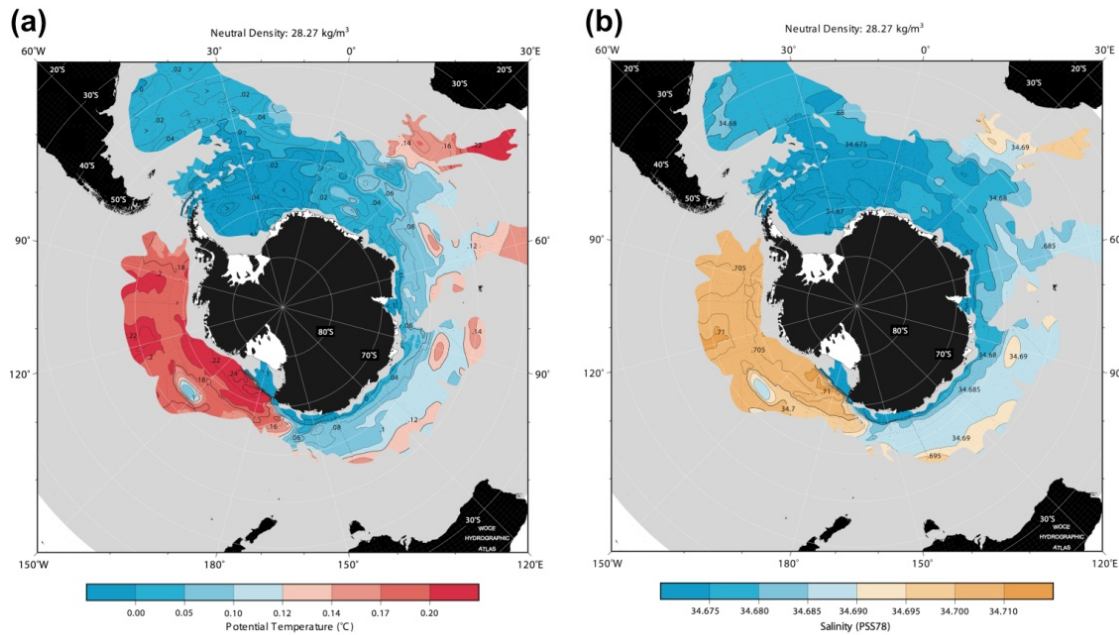
COASTAL POLYNYA



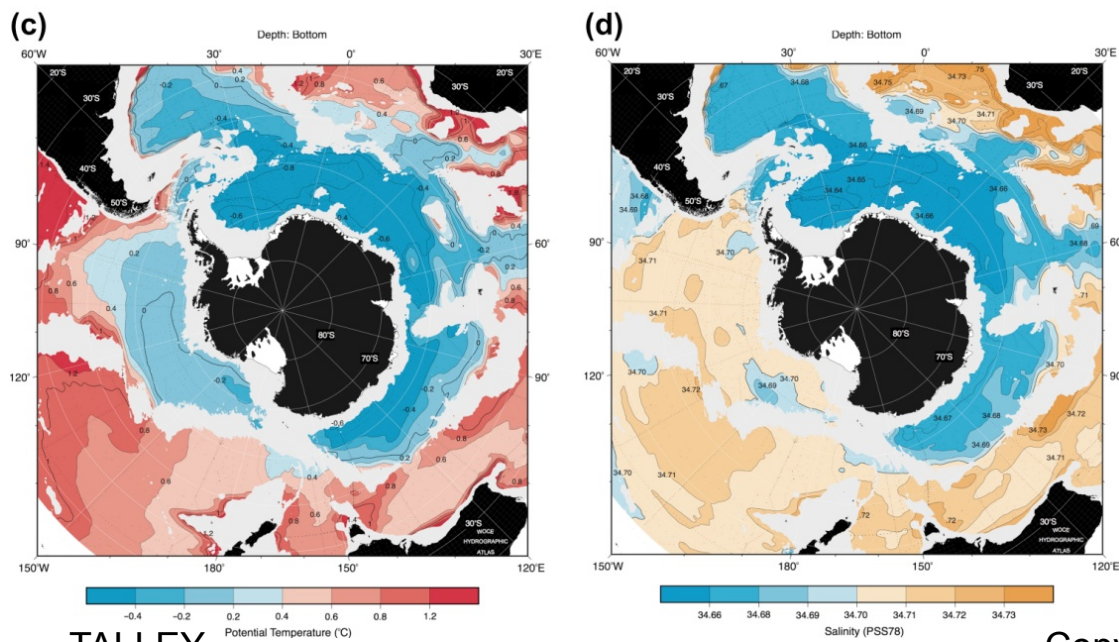


Antarctic latent heat polynyas: sea ice production, averaged over 1992-2001. This figure can also be found in the color insert. *Source: From Tamura et al. (2008).*

FIGURE 13.20

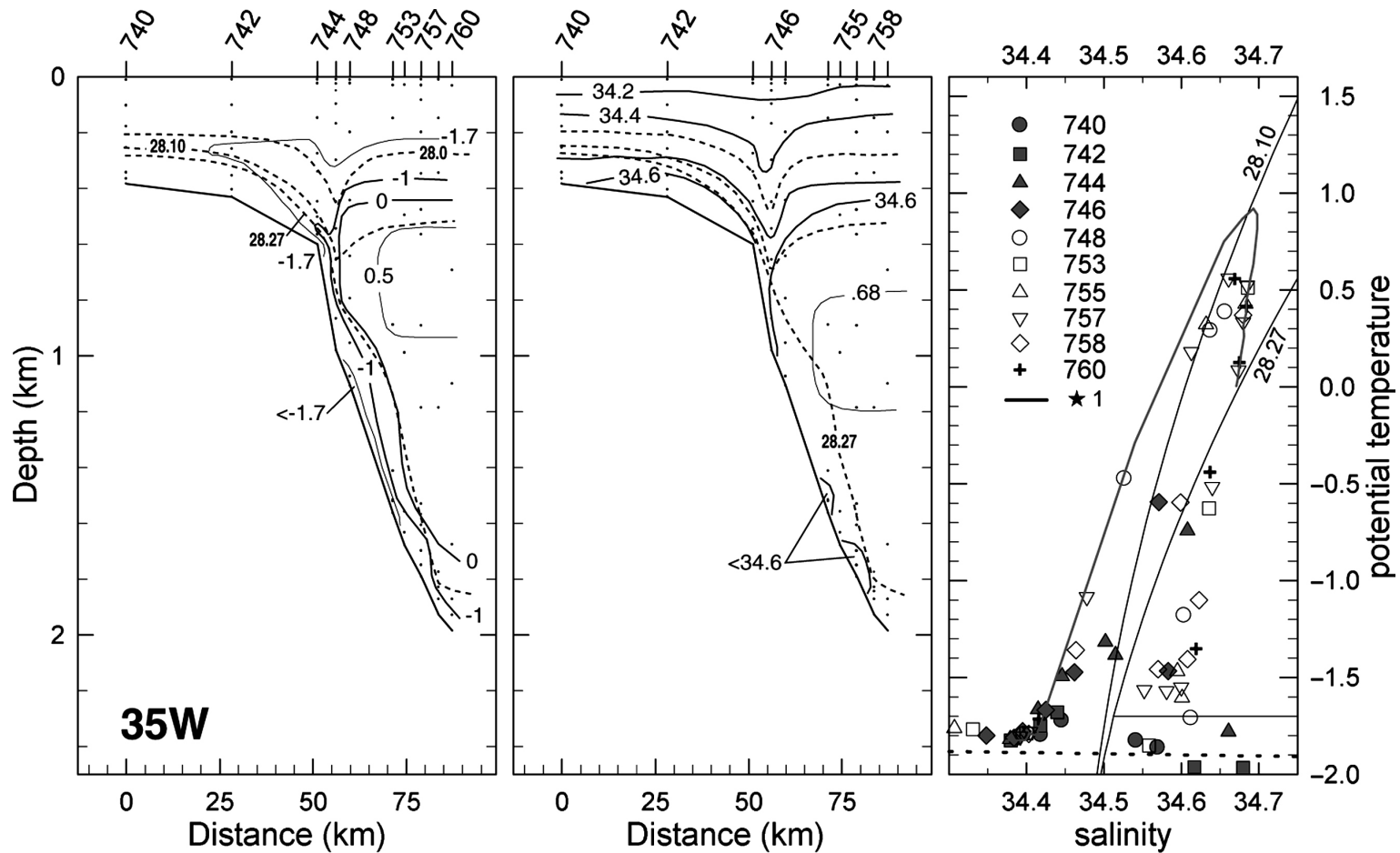


Properties on an Antarctic Bottom Water isopycnal (neutral density 28.27 kg m⁻³). (a) Potential temperature and (b) salinity. Bottom properties (depths greater than 3500 m): (c) potential temperature (°C) and (d) salinity. This figure can also be found in the color insert. *Source: From WOCE Southern Ocean Atlas, Orsi and Whitworth (2005).*



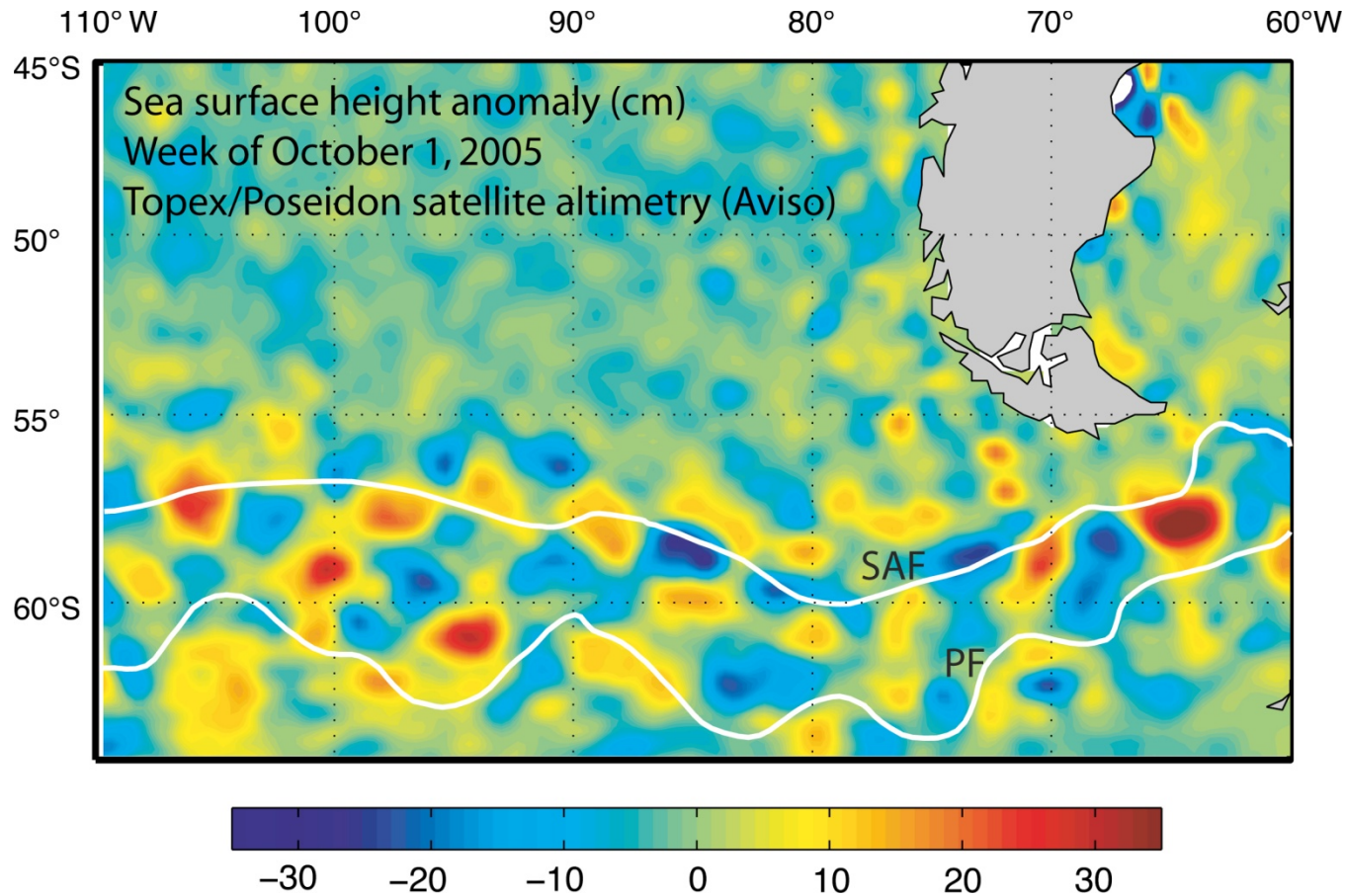
TALLEY

FIGURE 13.16



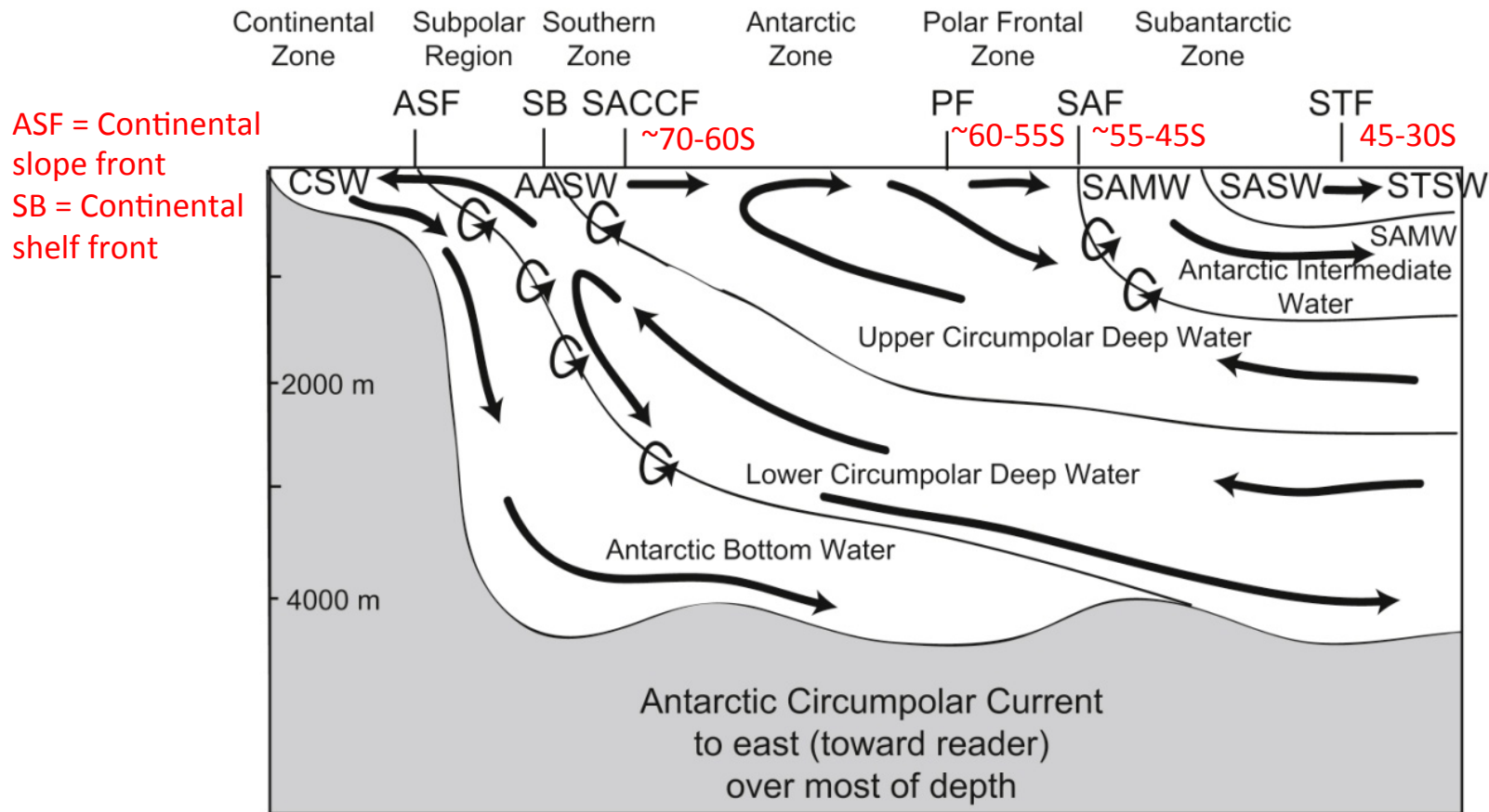
Vertical sections of (left) potential temperature and (center) salinity at about 35°W in the western Weddell Sea. (Right) Potential temperature versus salinity. Dashed contours in (left) and (center) are neutral density. Near-horizontal dashed line in right panel is the freezing point at 0 dbar. *Source: From Whitworth et al. (1998).*

FIGURE 13.17



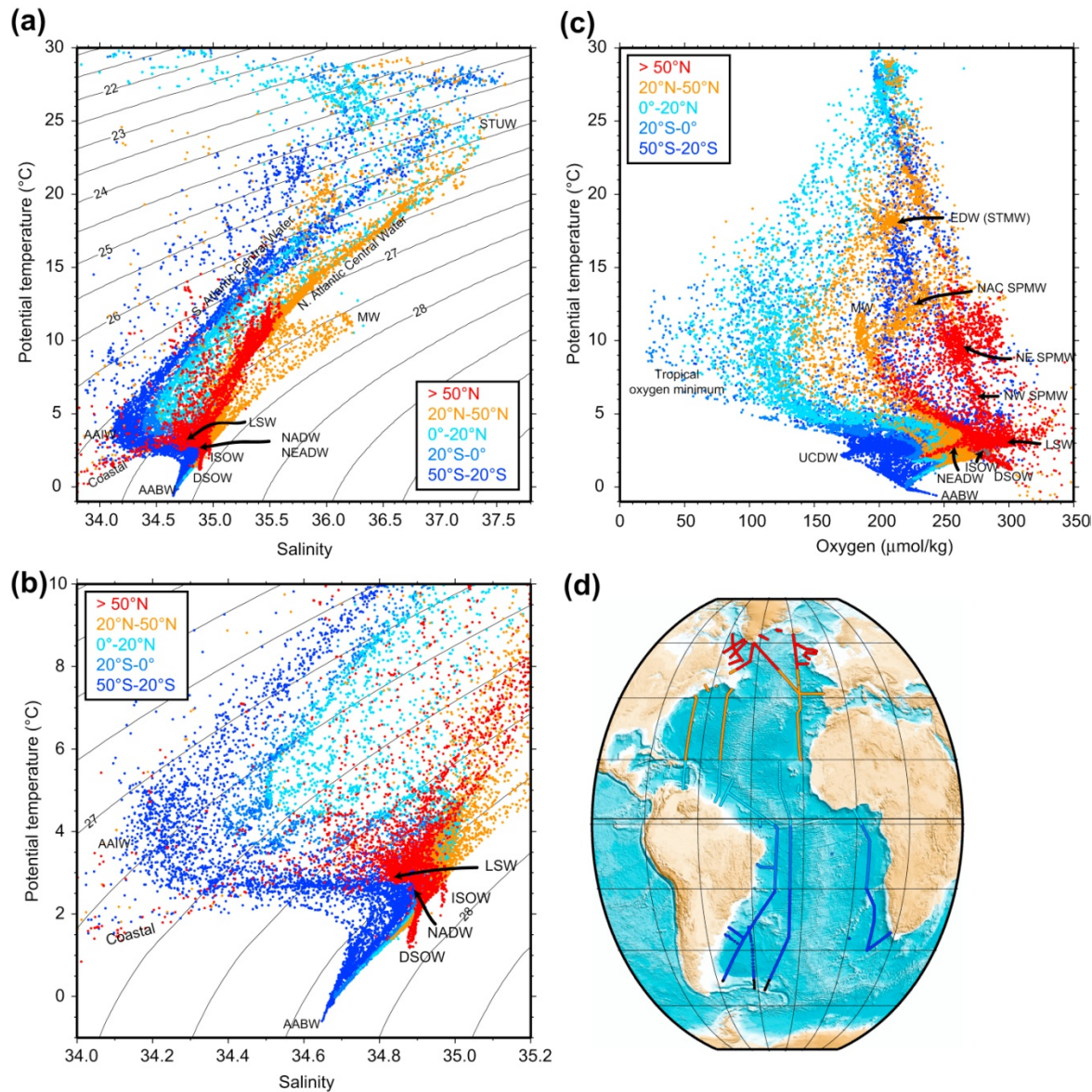
Snapshot of eddies in the southeast Pacific and Drake Passage: sea surface height anomalies (cm) for the week of October 1, 2005 from Topex/Poseidon altimetry (Aviso product). The climatological Subantarctic Front (SAF) and Polar Front (PF) are marked.

FIGURE 13.18



A schematic meridional section in the Southern Ocean showing the water masses, meridional circulation, fronts, and most zones. Acronyms: Continental Shelf Water (CSW), Antarctic Surface Water (AASW), Subantarctic Mode Water (SAMW), Subantarctic Surface Water (SASW), Subtropical Surface Water (STSW), Antarctic Slope Front (ASF), Southern Boundary (SB), Southern ACC Front (SACCF), Polar Front (PF), Subantarctic Front (SAF), and Subtropical Front (STF). After Speer, Rintoul, and Sloyan (2000).

FIGURE 13.4



Potential temperature ($^{\circ}\text{C}$) versus salinity for (a) full water column, and (b) water colder than 10°C . (c) Potential temperature versus oxygen for full water column. (d) Station location map. Colors indicate latitude range. Contours are potential density referenced to 0 dbar. Data are from the World Ocean Circulation Experiment (1988–1997). This figure can also be found in the color insert.

FIGURE 9.18