FLORIDA CURRENT, GULF STREAM, AND LABRADOR CURRENT

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Introduction

The swiftest oceanic currents in the North Atlantic are located near its western boundary along the coasts of North and South America. The major western boundary currents are (1) the Gulf Stream, which is the north-western part of the clockwise flowing subtropical gyre located between 10°N and 50°N (roughly); (2) the North Brazil Current, the western portion of the equatorial gyre located between the equator and 5°N; (3) the Labrador Current, the western portion of the counter-clockwise-flowing subpolar gyre located between 45°N and 65°N; and (4) a deep, swift current known as the Deep Western Boundary Current, which flows southward along the whole western boundary of the North Atlantic from the Labrador Sea to the equator at depths of around 1000–4000 m.

The swift western boundary currents are connected in the sense that a net flow of warmer upper ocean water (0–1000 m very roughly) passes northward through the Atlantic to the farthest reaches of the North Atlantic where the water is converted to colder, denser deep water that flows back southward through the Atlantic. This meridional overturning circulation, or thermohaline circulation as it is also known, occurs in a vertical plane and is the focus of much recent research that is resulting in new ideas about how water, heat, and salt are transported by ocean currents. The combination of northward flow of warm water and southward flow of cold water transports large amounts of heat northward, which is important for North Atlantic weather and climate.

History

The Florida Current, the part of the Gulf Stream flowing off Florida, was described by Ponce de León in 1513 when his ships were frequently unable to stem the current as they sailed southward. The first good chart of the Gulf Stream was published in 1769–1770 by Benjamin Franklin and Timothy Folger, summarizing the Nantucket ship captain's knowledge gained in their pursuit of the sperm whale along the edges of the Stream (Figure 1). By the early nineteenth century the major circulation patterns at the surface were charted and relatively well known. During that century, deep hydrographic and current meter measurements began to reveal aspects of the subsurface Gulf Stream. The first detailed series of hydrographic sections across the Stream were begun in the 1930s, which led to a much-improved description of its water masses and circulation. During World War II the development of Loran improved navigation and enabled scientists to identify and follow Gulf Stream meanders for the first time. Shipboard surveys revealed how narrow, swift, and convoluted the Gulf Stream was. Stimulated by these new observations, Henry Stommel in 1948 explained that the western intensification of wind-driven ocean currents was related to the meridional variation of the Coriolis parameter. Ten years later, Stommel suggested that cold, dense water formed in the North Atlantic in late winter does not flow southward along the seafloor in the mid-Atlantic but instead is constrained to flow southward as a Deep Western Boundary Current (DWBC). This prediction was soon verified by tracking some of the first subsurface acoustic floats in the DWBC off South Carolina. In the 1960s and 1970s, deep floats, and moored current meters began to provide some details of the complicated velocity fields in the Gulf Stream and DWBC. Satellite infrared measurements of sea surface temperature provided much information about the near-surface currents including temporal variations and eddies. In the 1980s and 1990s, surface drifters, subsurface floats, moored current meters, satellite altimetry, and various kinds of profilers were used to obtain long (few years) time series. These have given us our present understanding of western boundary currents, their transports, temporal variations, and role in transporting mass, heat and salt. Models of ocean circulation are playing an important role in helping to explore ocean processes and the dynamics that drive western boundary currents.

Generating Forces

Two main forces generate large-scale ocean currents including western boundary currents. The first is wind stress, which generates the large-scale oceanic gyres like the clockwise-flowing subtropical gyre

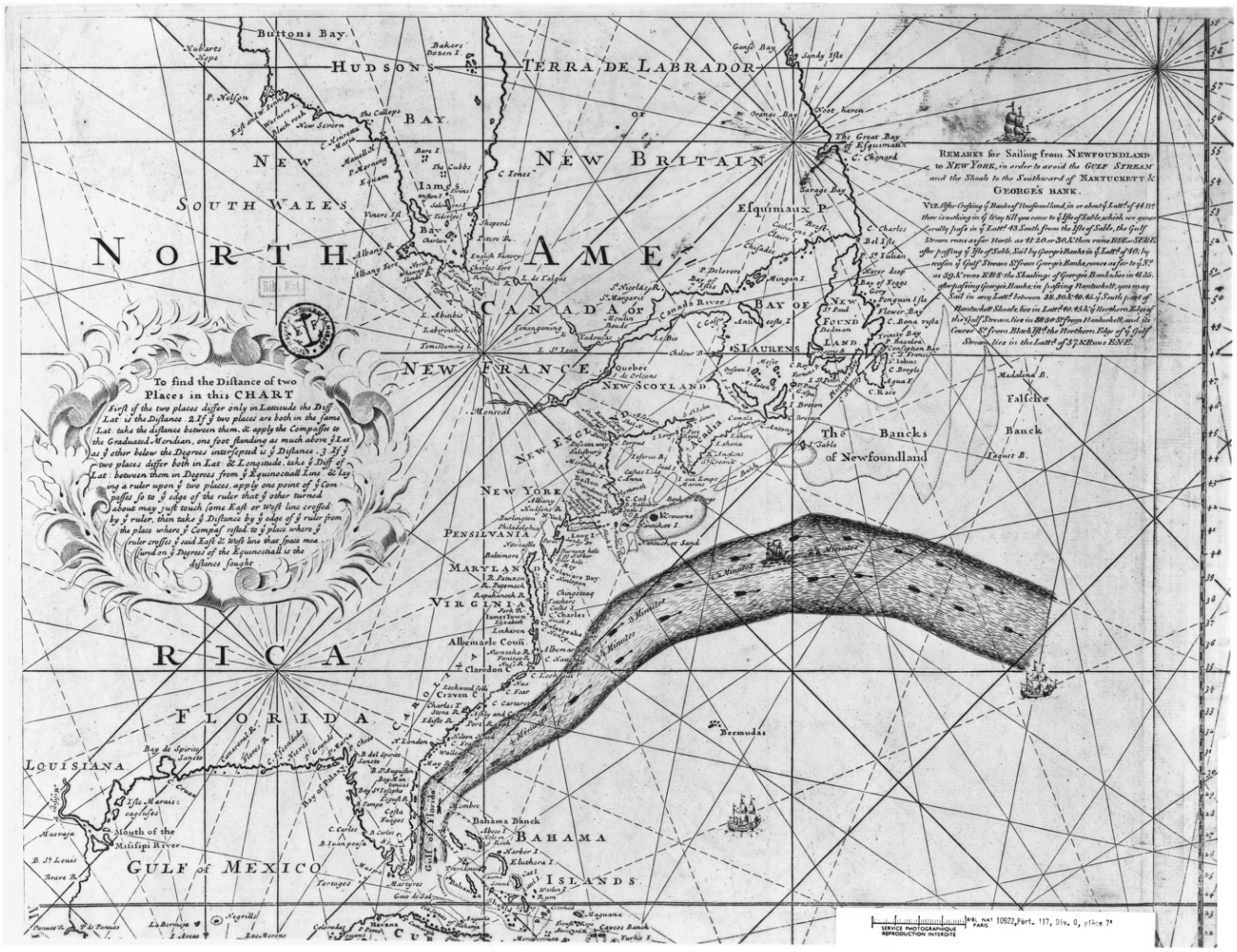

Figure 1 The Franklin–Folger chart of the Gulf Stream printed circa 1769–1770. This was the first good chart of the Stream and continues today to be a good summary of its mean speed, course, and width (assuming the charted width is the limit of the Stream's meanders). (See Richardson PL (1980) Benjamin Franklin and Timothy Folger's first printed chart of the Gulf Stream. *Science* 207: 643–645.)

centered in the upper part of the Atlantic (upper 1000 m roughly). The second is buoyancy forcing, which generates differences in water density by means of heating, cooling, precipitation, and evaporation and causes the large-scale meridional overturning circulation (MOC) – the northward flow of warmer less dense water and the southward flow of colder, denser water underneath. The rotation and spherical shape of the earth intensify currents along the western margins of ocean basins. The westward intensification is a consequence of the meridional poleward increase in magnitude of the vertical component of Earth's rotation vector, the Coriolis parameter. The vertical component is important because the oceans are stratified and much wider than they are deep.

In the Gulf Stream, the northward wind-driven gyre circulation and the northward-flowing upper part of the buoyancy-forced MOC are in the same direction and are additive. The relative amounts of transport in the Gulf Stream due to wind forcing and buoyancy forcing are thought to be roughly 2:1, although this subdivision is an oversimplification because the forcing is complicated and the Gulf Stream is highly nonlinear. In the vicinity of the Guyana Current ($\sim$10°N) the upper layer MOC is counter to and seems to overpower the wind-driven tropical gyre circulation, resulting in northward flow, where southward flow would be expected from wind stress patterns alone. Farther south in the North Brazil Current (0–5°N), the western boundary part of the clockwise-flowing wind-driven equatorial gyre is in the same direction as the MOC, and their transports add. Along the western boundary of the Labrador Sea, the southward-flowing part of the subpolar gyre, the Labrador Current, is in the same direction as the

DWBC, resulting in a top–bottom southward-flowing western boundary current.

Gulf Stream System

The Gulf Stream System is an energetic system of swift fluctuating currents, recirculations, and eddies. The swiftest surface currents of ~5 knots or $250\,cm\,s^{-1}$ are located where the Stream is confined between Florida and the Bahamas. In this region and sometimes farther downstream, the Stream is known as the Florida Current. Off Florida, the Gulf Stream extends to the seafloor in depths of 700 m and also farther north along the Blake Plateau in depths of 1000 m. Near Cape Hatteras, North Carolina (35°N), the Stream leaves the western boundary and flows into deep water (4000–5000 m) as an eastward jet (Figure 2). The Stream's departure point from the coast is thought to be determined by the large-scale wind stress pattern, interactions with the southward-flowing DWBC, and inertial effects. The Gulf Stream flows eastward near 40°N toward the Grand Banks of Newfoundland, where part of the Stream divides into two main branches that continue eastward and part returns westward in recirculating gyres located north and south of the mean Gulf Stream axis.

The first branch, the North Atlantic Current, flows northward along the eastern side of Grand Banks as a western boundary current reaching 50°N, where it meets the Labrador Current, turns more eastward, and crosses the mid-Atlantic Ridge. Part of this flow circulates counterclockwise around the subpolar gyre and part enters the Nordic Seas. This latter part eventually returns to the Atlantic as cold, dense overflows that merge with less dense intermediate and deep water in the Labrador Sea and flow southward as the DWBC.

The second branch of the Gulf Stream flows southeastward from the region of the Grand Banks, crosses the mid-Atlantic Ridge, and flows eastward near 34°N as the Azores Current. Water from this and other more diffuse flows circulates clockwise around the eastern side of the subtropical gyre and returns westward to eventually reform into the Gulf Stream. A north-westward flow along the eastern side of the Antilles Islands is known as the Antilles Current. It is predominantly a subsurface thermocline flow.

Water flowing in the Gulf Stream comes from both the westward-flowing return current of the subtropical gyre and from the South Atlantic. Roughly half of the transport of the Florida Current is South Atlantic water that has been advected through the Gulf of Mexico and the Caribbean from the North Brazil Current.

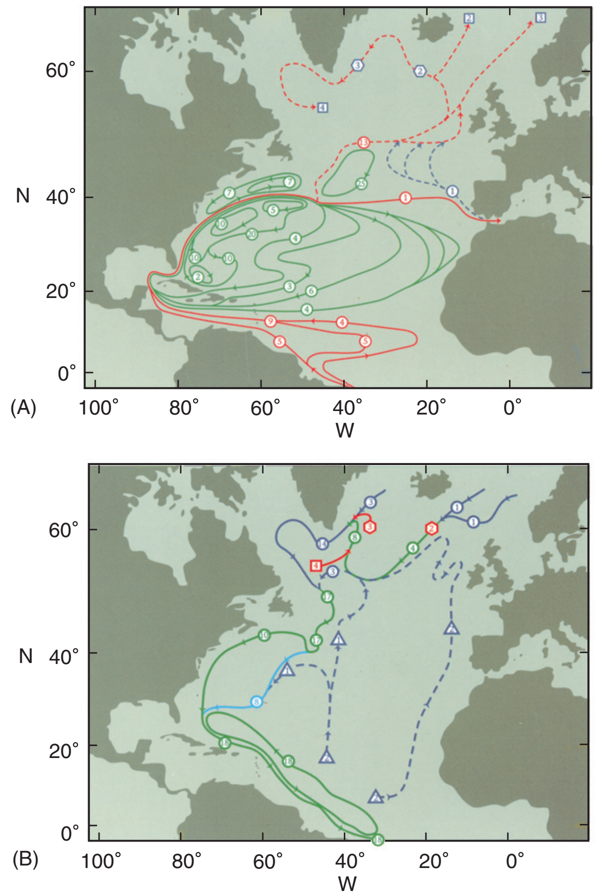

Figure 2 (A) Schematic showing the transport of the upper layer (temperatures greater than around 7°C) North Atlantic circulation (in Sverdrups,1 $Sv = 10^6\ m^3\,s^{-1}$). Transports in squares denote sinking and those in hexagons denote entrainment. Red lines show the upper layer flow of the meridional overturning circulation. The blue boxes attached to dashed lines indicate that significant cooling may occur. Solid green lines characterize the subtropical gyre and recirculations as well as the Newfoundland Basin Eddy. Dashed blue lines indicate the addition of Mediterranean Water to the North Atlantic. (B) Schematic circulation showing the transport in Sverdrups of North Atlantic Deep Water (NADW). Green lines indicate transports of NADW, dark blue lines and symbols denote bottom water, and red lines upper layer replacement flows. Light blue line indicates a separate mid-latitude path for lower NADW. The square represents sinking, hexagons entrainment of upper layer water, and triangles with dashed lines water mass modification of Antarctic Bottom Water. (Reproduced from Schmitz (1996).)

Current Structure

The Gulf Stream is a semicontinuous, narrow (~100 km wide) current jet with fastest speeds of $200–250\,cm\,s^{-1}$ located at the surface decreasing to around $20\,cm\,s^{-1}$ near 1000 m depth (Figure 3). The mean velocity of the Stream extends to the seafloor even in depths below 4000 m with a mean velocity of a few centimeters per second. The deep flow field

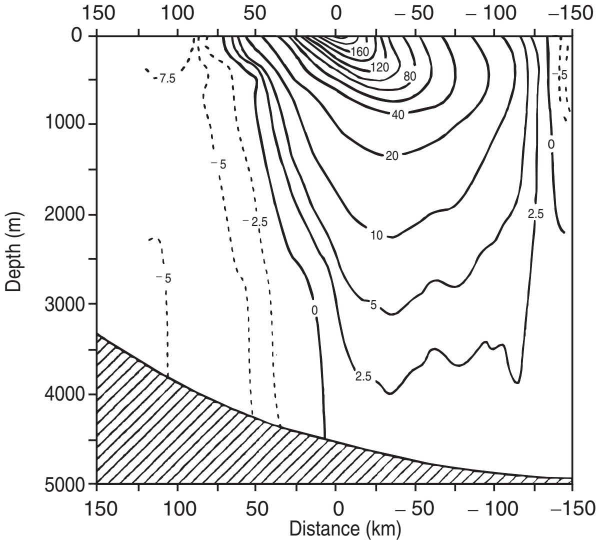

Figure 3 Downstream speed (positive) (cm s^{-1}) of the Gulf Stream at 68°W measured with current meters. (Adapted from Johns *et al.* (1995).)

under the Stream is complex and not just a simple deep extension of the upper layer jet.

The Stream flows along the juncture of the warm water in the Sargasso Sea located to the south and the cold water in the Slope Water region to the north (Figure 4). The maximum temperature gradient across the Stream is located near a depth of 500 m and amounts to around 10°C. Maximum surface temperature gradients occur in late winter when the Slope Water is coolest and the Stream advects warm tropical water northward. This relatively warm water is clearly visible in infrared images of the Stream (Figure 5). The sea surface slopes down northward across the Gulf Stream by around 1 m due to the different densities of water in the Sargasso Sea and Slope Water region. The surface slope has been measured by satellite altimeters and used to map the path and fluctuations of the Stream.

Variability

The Gulf Stream jet is unstable. It meanders north and south of its mean position forming convoluted paths that seem to have a maximum amplitude of around 200 km near 55°W (Figure 6). The most energetic meanders propagate downstream with a period of around 46 days and wavelength near 430 km. Frequently the edges of individual large meanders merge and coherent pieces of the Stream separate from the main current in the form of large eddies or current rings. Gulf Stream rings are typically 100–300 km in diameter. Those north of the Stream rotate clockwise and those south of the Stream rotate counterclockwise. As rings form on one side of the Stream, they trap in their centers, water from the opposite side of the Stream. Cold core rings are located to the south and warm core rings to the north. Once separate from the Stream, rings tend to translate westward at a few centimeters per second. Often they coalesce with the Stream after lifetimes of several months to years. The formation of rings is an energy sink for the swift Gulf Stream jet and also acts to decrease the mean temperature gradient across the Stream.

Infrared images and other data show that the Gulf Stream region is filled with meanders, rings, and smaller-scale current filaments and eddies that appear to be interacting with each other (Figure 5). The picture of the Gulf Stream as a continuous current jet is probably an oversimplification. Often various measurements of the Stream are combined and schematic pictures are drawn of its 'mean' characteristics. Although no such thing as a 'mean' occurs in reality, the schematics are very useful for simplifying very complex phenomena and for showing conceptual models of the Stream. One of the first such schematics by Franklin and Folger is shown in Figure 1.

The swift current speeds in the Gulf Stream in combination with its energetic meanders, rings, and other eddies result in very large temporal current fluctuations and very high levels of eddy kinetic energy (EKE) that coincide with the Gulf Stream between 55°W and 65°W (Figure 7A). Roughly 2/3 of the EKE is a result of the meandering Stream. Peak values of EKE near the surface are over 2000 cm^2 s^{-2}. The region of high EKE extends down to the sea floor underneath the Stream where values are in excess of 100 cm^2 s^{-2}, roughly 100 times larger than values in the deep Sargasso Sea (Figure 7B). EKE is a measure of how energetic time variations and eddies are in the ocean; EKE is usually much larger than the energy of the mean currents which suggests that eddies are important to ocean physics at least where the largest values of EKE are found.

The Gulf Stream varies seasonally and interannually, but because of energetic eddy motions and the required long time series, the low-frequency variability has only been documented in a very few places. The amplitude of the seasonal variation of the Florida Current transport is relatively small, around 8% of the mean transport, with maximum flow occurring in July–August. There is little evidence for longer-term variations in the Florida Current. Interannual variations in the wind patterns over the North Atlantic have been observed as well as variations in hydrographic properties and amounts of Labrador Sea Water formed. Present research is

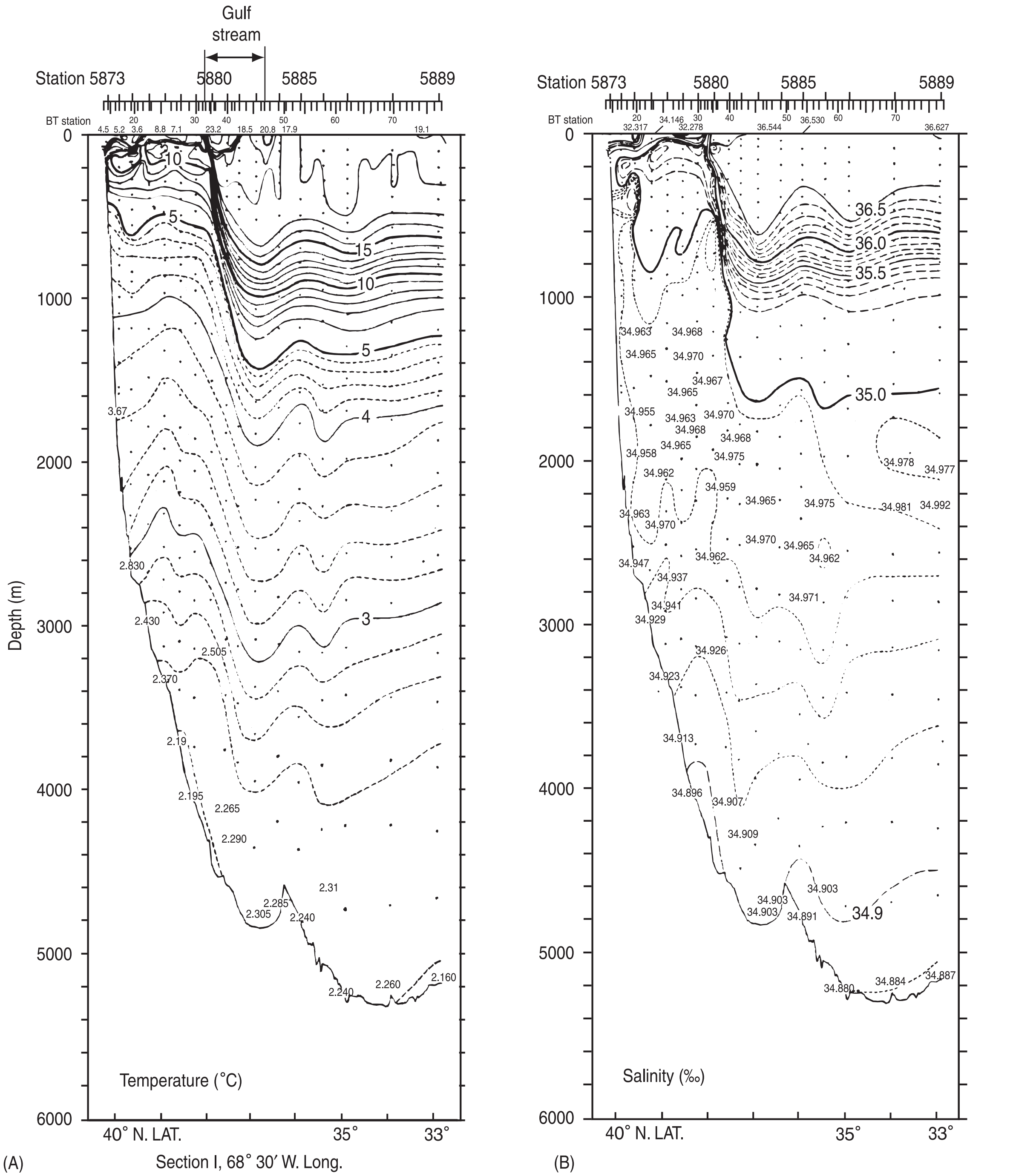

Figure 4 Temperature (A) and salinity (B) sections across the Gulf Stream near 68°W. (Adapted from Fuglister FC (1963) Gulf Stream '60. *Progress in Oceanography* 1: 265–373.)

investigating these climate variations of the ocean and atmosphere.

Transport

The volume transport of the Florida Current or amount of water flowing in it has been measured to be around 30 Sv where 1 Sverdrup (Sv) $= 10^6\,m^3\,s^{-1}$. This transport is around two thousand times the annual average transport of the Mississippi River into the Gulf of Mexico. As the Stream flows northward, its transport increases 5-fold to around 150 Sv located south of Nova Scotia. Most of the large transport is recirculated westward in recirculating gyres located

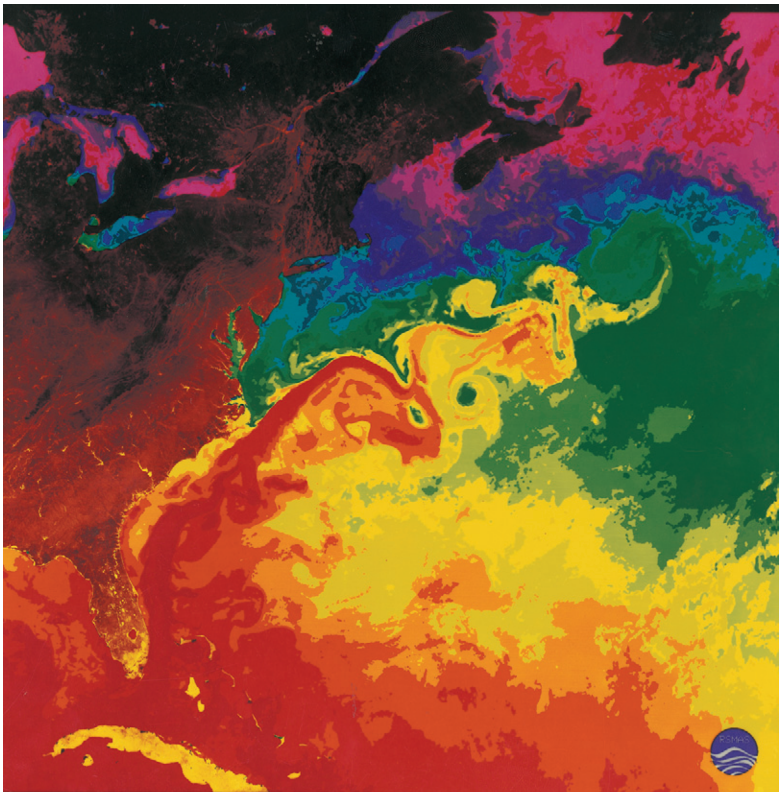

Figure 5 Satellite infrared image showing sea surface temperature distribution. Warm water (orange-red) is advected northward in the Gulf Stream. Meanders and eddies can be inferred from the convoluted temperature patterns. Image courtesy of O. Brown, R. Evans and M. Carle, University of Miami, Rosenstiel School of Marine and Atmospheric Science.

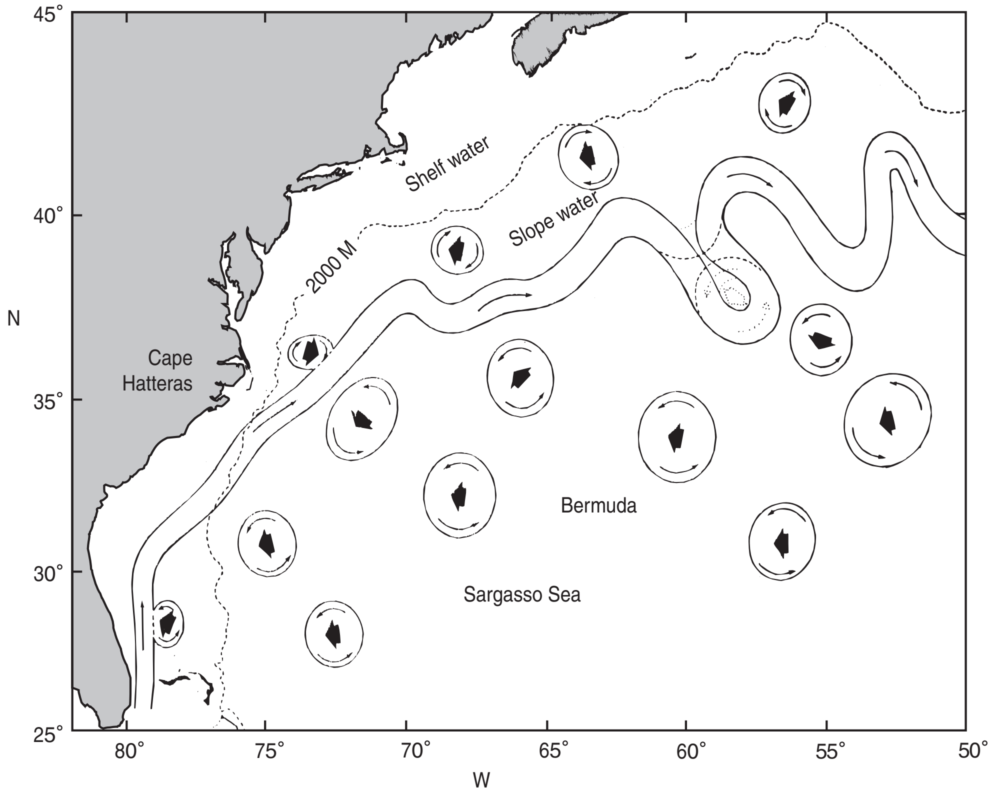

Figure 6 Schematic representation of the instantaneous path of the Gulf Stream and the distribution and movement of rings. Each year approximately 22 warm core rings form north of the Gulf Stream and 35 cold core rings form south of the Stream. (Reproduced from Richardson PL (1976) Gulf Stream rings. *Oceanus* 19(3): 65–68.)

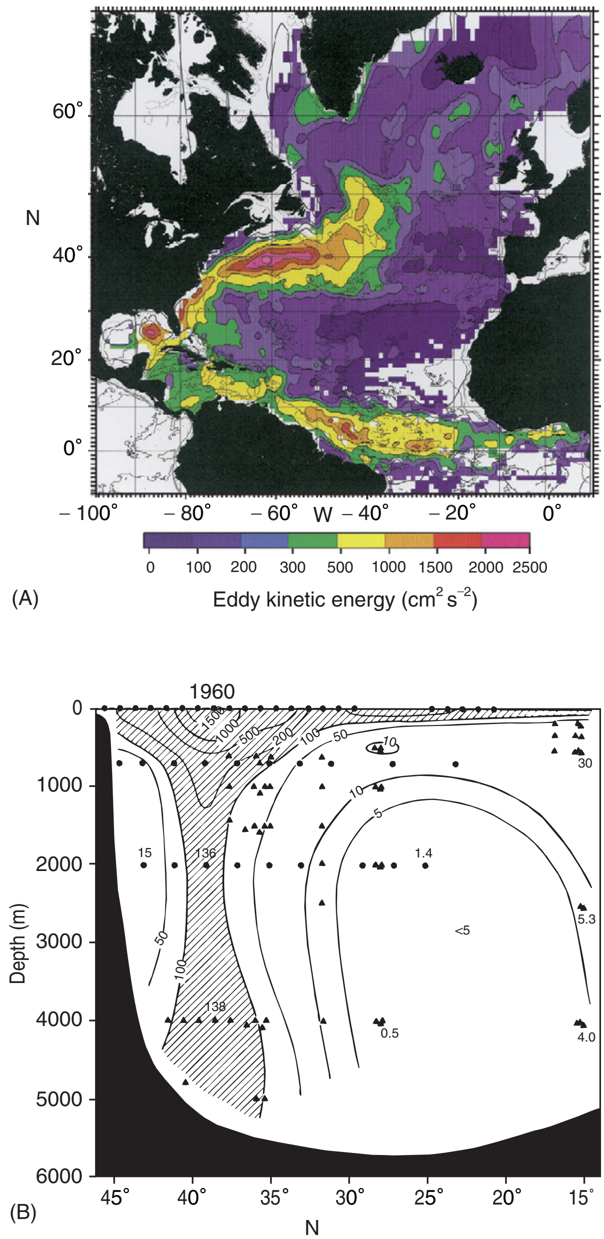

Figure 7 (A) Horizontal distribution of eddy kinetic energy (EKE) in the North Atlantic based on a recent compilation of surface drifter data. EKE is equal to $\frac{1}{2}(\overline{u'^2} + \overline{v'^2})$ where u' and v' are velocity fluctuations from the mean velocity calculated by grouping drifter velocities into small geographical bins. High values of EKE ($cm^2\,s^{-2}$) coinciding with the Gulf Stream are 10 times larger than background values in the Sargasso Sea. (Courtesy of D. Fratantoni, WHOI.) (B) Vertical section of EKE ($cm^2\,s^{-2}$) across the Gulf Stream system and subtropical gyre near 55°W based on surface drifters, SOFAR floats at 700 m and 2000 m (dots) and current meters (triangles). High values of EKE coincide with the mean Gulf Stream axis located near 40°N (roughly). (Adapted from Richardson PL (1983) A vertical section of eddy kinetic energy through the Gulf Stream system. *Journal of Geophysical Research* 88: 2705–2709.)

north and south of the Gulf Stream axis (Figure 8). The 150 Sv is much larger than that estimated for the subtropical gyre from wind stress (~30–40 Sv) and the net MOC (~15 Sv). Numerical models of the Gulf Stream suggest that the large increase in transport and the recirculating gyres are at least partially generated by the Stream's energetic velocity fluctuations. The region of largest EKE coincides with the maximum transport and recirculating gyres both in the ocean and in models. Inertial effects and buoyancy forcing are also thought to contribute to the recirculating gyres.

The velocity and transport of the Stream can be subdivided into two parts, a vertically sheared or baroclinic part consisting of fast speeds near the surface decreasing to zero velocity at 1000 m, and a constant or barotropic part without vertical shear that extends to the sea floor underneath the Stream. The baroclinic part of the Stream remains nearly constant (~50 Sv) with respect to distance downstream from Cape Hatteras, but the barotropic part more than doubles, from around 50 Sv to 100 Sv, causing the large increase in transport. The lateral meandering of the Stream and the north and south recirculating gyres are also highly barotropic and extend to the seafloor.

Estimates of the transport of the North Atlantic Current east of Newfoundland are also as large as 150 Sv. A recirculating gyre, known as the Newfoundland Basin Eddy, is observed to the east of this current.

North Brazil Current

The North Brazil Current (NBC) is the major western boundary current in the equatorial Atlantic. The NBC is the northward-flowing western portion of the clockwise equatorial gyre that straddles the equator. Near 4°N the mean transport of the NBC is around 26 Sv, which includes 3–5 Sv of flow over the Brazilian shelf. Maximum near-surface velocities are over 100 cm s^{-1}.

Large seasonal changes in near-equatorial currents are forced by the annual meridional migration of the Intertropical Convergence Zone that marks the boundary of the north-east tradewinds located to the north and the south-east trades to the south. The meridional migration of the winds causes large annual variations of wind stress over the tropical Atlantic. During summer and fall most of the NBC turns offshore or retroflects near 6°N and flows eastward between 5 to 10°N in the North Equatorial Countercurrent. During July and August the transport of the NBC increases to 36 Sv; most of the transport lies above 300 m, but the northward

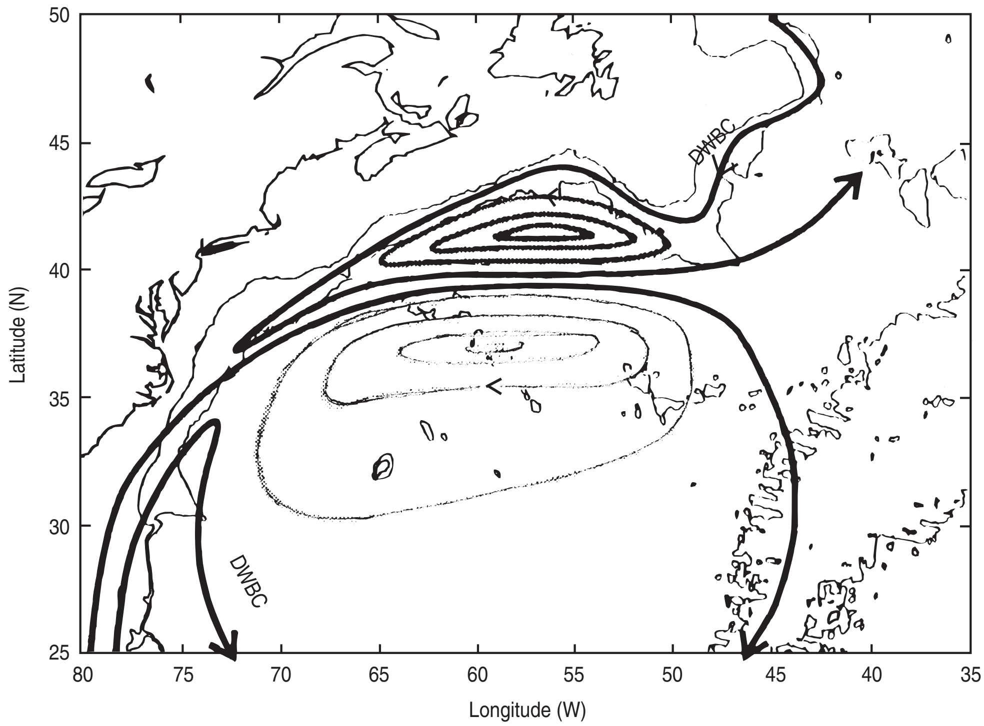

Figure 8 Schematic circulation diagram showing average surface to bottom transport of the Gulf Stream, the northern and southern recirculating gyres, and the DWBC. Each streamline represents approximately 15 Sv. Because of the vertical averaging, the DWBC looks discontinuous in the region where it crosses under or through the Gulf Stream near Cape Hatteras. (Adapted from Hogg NG (1992) On the transport of the Gulf Stream between Cape Hatteras and the Grand Banks. *Deep-Sea Research* 39: 1231–1246.)

current extends down to roughly 800 m and includes Antarctic Intermediate Water. In April and May the transport decreases to 13 Sv and the NBC becomes weaker, more trapped to the coast, and more continuous as a boundary current. At this time the countercurrent also weakens.

Occasionally, 3–6 times per year, large 400-km diameter pieces of the retroflection pinch off in the form of clockwise-rotating current rings. NBC rings translate northward along the western boundary 10–20 cm s^{-1} toward the Caribbean, where they collide with the Antilles Islands. The northward transport carried by each ring is around 1 Sv. During fall–spring the western boundary current region north of the retroflection is dominated by energetic rings.

Amazon River Water debouches into the Atlantic near the equator, is entrained into the western side of the NBC, and is carried up the coast. Some Amazon Water is advected around the retroflection into the countercurrent and some is caught in rings as they pinch off. Farther north near 10°N the Orinoco River adds more fresh water to the north-westward-flowing currents.

The path of South Atlantic water toward the Gulf Stream is complicated by the swift, fluctuating currents. Some northward transport occurs in alongshore flows, some in NBC rings, and some by first flowing eastward in the countercurrent, then counterclockwise in the tropical gyre, and then westward in the North Equatorial Current.

The South Atlantic Water and Gulf Stream recirculation merge in the Caribbean. Water in the Caribbean Current is funneled between Yucatan and Cuba into the swift narrow ($\sim$100 km wide) Yucatan Current. The flow continues in the Gulf of Mexico as the Loop Current, and then exits through the Straits of Florida as the Florida Current. Roughly once per year a clockwise rotating current ring pinches off from the Loop Current in the Gulf of Mexico and translates westward to the western boundary, where a weak western boundary current is observed.

Labrador Current

The Labrador Current is formed by very cold -1.5°C water from the Baffin Island Current and a branch of the West Greenland Current, which merge on the western side of the Labrador Sea. The current flows southward from Hudson Strait to the

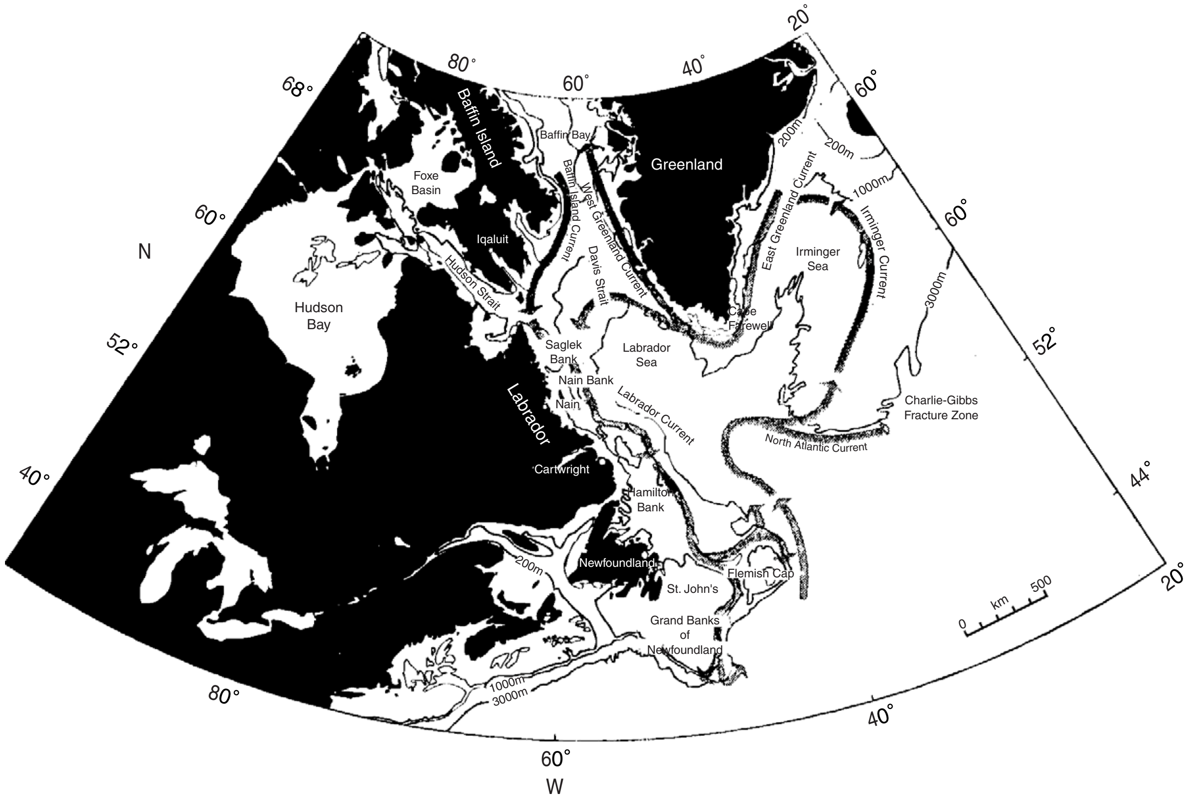

Figure 9 Schematic figure showing the North Atlantic subpolar gyre circulation and the Labrador Current. (Reproduced from Lazier and Wright (1993).)

southern edge of the Grand Banks of Newfoundland (Figure 9). The Labrador Current consists of two parts. The first ~ 11 Sv is located over the shelf and upper slope and is concentrated in a main branch over the shelf break. This part is highly baroclinic and is thought to be primarily buoyancy-driven by fresh water input from the north. The second part, the deep Labrador Current, lies farther seaward over the lower continental slope, is more barotropic, and extends over the full water depth down to around 2500 m. Below roughly 2000 m is Nordic Seas overflow water, which also flows southward along the western boundary. The deep Labrador Current is the western portion of the subpolar gyre, which has a transport of around 40 Sv.

Most of the Labrador Current water leaves the boundary near the Grand Banks, part entering a narrow northward-flowing recirculation and part flowing eastward in the subpolar gyre. Very sharp horizontal gradients in temperature and salinity occur where cold, fresh Labrador Current Water is entrained into the edge of the North Atlantic Current. Some Labrador Current Water passes around the Grand Banks and continues westward along the shelf and slope south of New England and north of the Gulf Stream (Figure 10).

Deep Western Boundary Current (DWBC)

The DWBC flows southward along the western boundary from the Labrador Sea to the equator. Typical velocities are 10–20 cm s^{-1} and its width is around 100–200 km. It is comprised of North Atlantic Deep Water that originates from very cold, dense Nordic Seas overflows and from less cold and less dense intermediate water formed convectively in the Labrador Sea in late winter. The DWBC is continuous in that distinctive water properties like the high freon content in the overflow water and in Labrador Sea Water have been tracked southward to the equator as plumes lying adjacent to the boundary. However, the DWBC is discontinuous in that it is flanked by relatively narrow sub-basin-scale recirculating counterflows that exchange water with the DWBC and recirculate DWBC water back northward. The net southward transport of the DWBC is thought to be around 15 Sv, but the measured southward transport is often two or three times that, the excess over 15 Sv being recirculated locally.

Near the Grand Banks of Newfoundland, part of the DWBC water leaves the boundary and divides

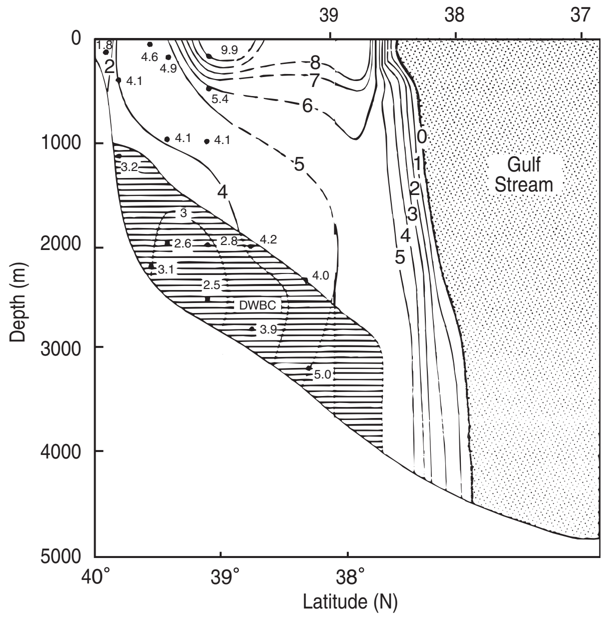

Figure 10 Vertical section near 68°W of mean zonal currents in the Slope Water region north of the Gulf Stream. Plotted values are westward velocity in $cm\,s^{-1}$. The region of the DWBC is indicated schematically by light lines. (Adapted from Johns *et al.* (1995).)

into a northward-flowing recirculation and the eastward-flowing subpolar gyre circulation. The other part flows around the Grand Banks and westward inshore of the Gulf Stream. Between the Grand Banks and Cape Hatteras, the DWBC coincides with the northern recirculating gyre (or Slope Water gyre), which also flows westward there (Figure 10). Near Cape Hatteras the DWBC encounters the deep Gulf Stream. Most of the deeper part of the DWBC seems to flow continuously south-westward underneath the mean axis of the Stream, but most of the water in the upper part of the DWBC appears to be entrained into the deep Gulf Stream and flows eastward. Some of this water recirculates in the northern recirculating gyre, and some crosses the mean axis of the Stream, recirculates westward south of the Stream toward the western boundary, and continues southward. The formation of energetic Gulf Stream meanders and pinched-off current rings is probably an important mechanism by which DWBC water passes across or through the mean axis of the Stream.

See also

Benguela Current. Brazil and Falklands (Malvinas) Currents. Mesoscale Eddies. Wind Driven Circulation.

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