CURRENT SYSTEMS IN THE ATLANTIC OCEAN

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Introduction

By the late nineteenth century our present view of the Atlantic Ocean surface circulation had already been largely worked out. The voyages of discovery brought startling observations of many of the important surface currents. During the twentieth century the focus turned to a detailed description of the surface currents and the investigation of the subsurface currents. Recently, much attention has been focused on climate research as it became clear that climate goes through long period variability and can affect our lives and prosperity. The physical climate system is controlled by the interaction of atmosphere, ocean, land and sea ice, and land surfaces. To understand the influence of the ocean on climate, the physical processes and especially the ocean currents storing and transporting heat need to be thoroughly investigated. Since the end of the twentieth century, the general circulation of the Atlantic Ocean has been considered in a climatological context. A new picture emerged with the North Atlantic Ocean being seen not only as relevant to the climate of Europe, but for its influence on the entire globe due to its unique thermohaline circulation. Its warm upper-ocean currents transport mass and heat, originating in part from the Pacific and Indian Oceans, towards the north in the South-Atlantic and the North Atlantic. Cold deep waters of the North Atlantic flow southward, cross the South Atlantic, and are exported into the Indian and even the Pacific Oceans. The research focus on ocean currents in the Atlantic Ocean at the beginning of the new millennium will be further investigation of the mean surface and deep currents of the Atlantic and its variability on short-term to decadal timescales, so that the ocean's role in climate change can be better understood.

Basin Structure

The Atlantic Ocean extends both into the Arctic and Antarctic regions, giving it the largest meridional extent of all oceans. The north–south extent from Bering Strait to the Antarctic continent is more than 21 000 km, while the largest zonal distance from the Gulf of Mexico to the coast of north-west Africa is only about 8300 km. Here the Atlantic Ocean is described between the northern polar circle and the southern tip of South America at 55°S (see **Figure 1**). In the north, the Davis Strait between northern Canada and west Greenland separates the Labrador Sea from Baffin Bay to the north of Davis Strait. The Denmark Strait between east Greenland and Iceland, and the ridges between Iceland and Scotland separate the Irminger Basin and the Iceland Basin from the Greenland Sea and Norwegian Sea. In the south a line from the southern tip of South America to the southern tip of South Africa separates the South Atlantic Ocean from the Southern Ocean. Although there is no topographic justification for this separation, defining a southern ocean around Antarctica allows the separate investigation of the Antarctic Circumpolar Current and the processes near Antarctica as a whole. The Atlantic Ocean has the largest number of adjacent seas, and the larger ones are discussed in other articles (*see* **Baltic Sea Circulation; Current Systems in the Mediterranean Sea;** and **North Sea Circulation.**)

The Mid-Atlantic Ridge, which in many parts rises to <2000 m depth and reaches the 3000 m depth contour nearly everywhere, is located zonally in most places near the middle of the Atlantic and divides the Atlantic Ocean into a series of eastern and western basins (**Figure 1**). The basin names presented in **Figure 1** are only the major ones; in more detailed investigations of special regions many more topographically identified structures exist with their related names. The major topographic features of the Atlantic strongly affect the deep currents of the deep and bottom water masses, either by blocking or guiding the flow. The Walvis Ridge off south-west Africa limits the northward flow of Antarctic Bottom Water (AABW) in the Cape Basin and consequently the major northward flow of AABW takes place in the western basins. Although the Rio Grande Rise between the Argentina Abyssal Plain and the Brazil Basin disturbs a smooth northward spreading of the AABW in the western basins, the Vema and Hunter Channels within the Rio Grande Rise are deep and wide enough to allow a continuous northward flow. The Romanche Fracture Zone at the equator allows part of the AABW to enter the eastern basins of the Atlantic, where the AABW spreads poleward in both hemispheres.

Once a water mass is formed, there is a conservation of its angular momentum, or rather potential

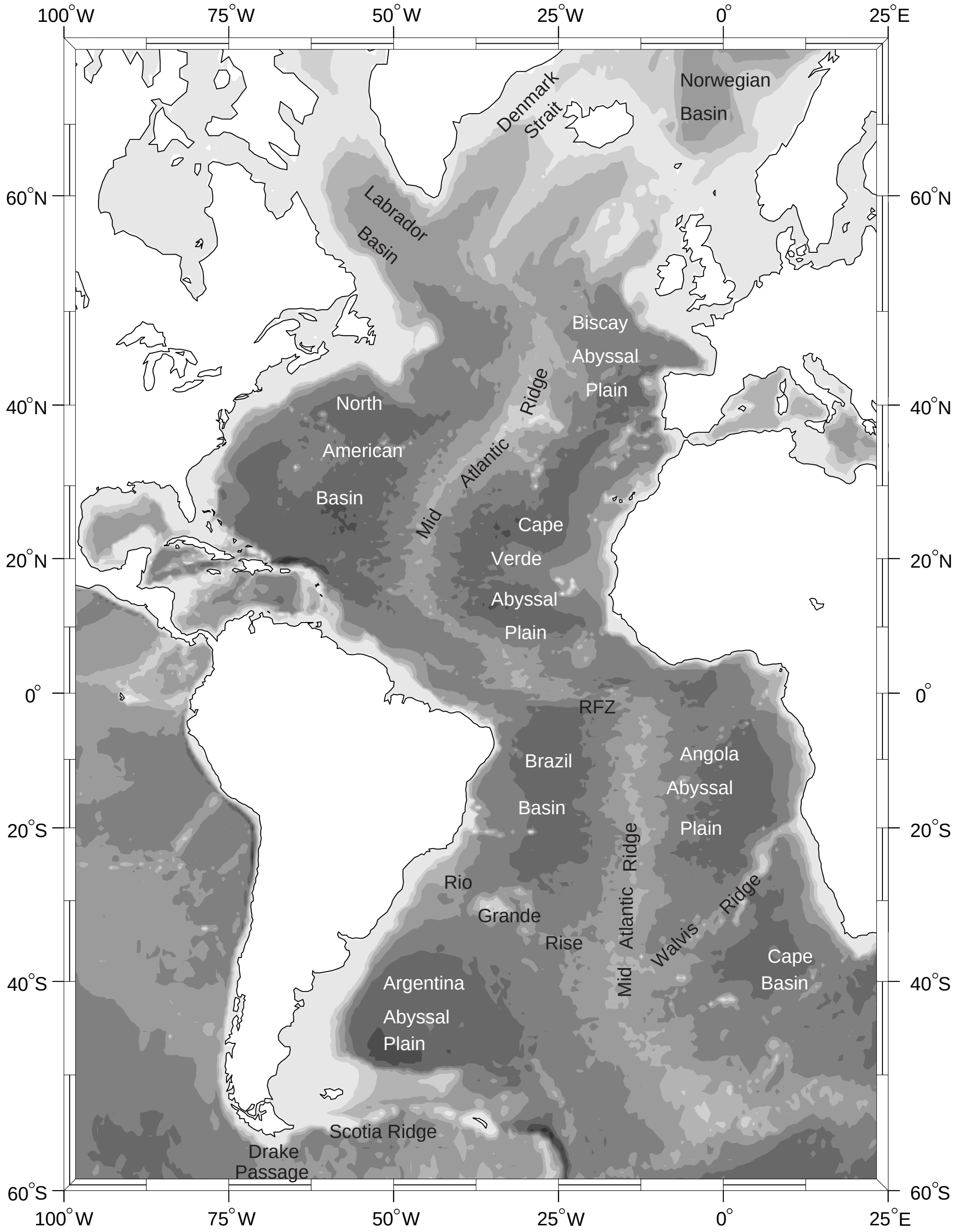

Figure 1 Topography of the Atlantic Ocean with large-scale depth contours in 1000 m steps. RFZ, Romanche Fracture Zone.

vorticity. For large-scale motions, in the interior of the ocean, potential vorticity reduces to $f/h = \text{constant}$ (where f is the Coriolis parameter and h the water depth). From this expression we can predict which way a current will swing on passing over bottom irregularities – equatorward over ridges and poleward over troughs in both hemispheres. A prominent example is the interaction between the relatively narrow Drake Passage south of the South American continent and the Scotia Ridge, which connects Antarctica with South America and contains numerous islands, located about 2000 km east of Drake Passage. The Antarctic Circumpolar Current accelerates to pass through the Drake Passage,

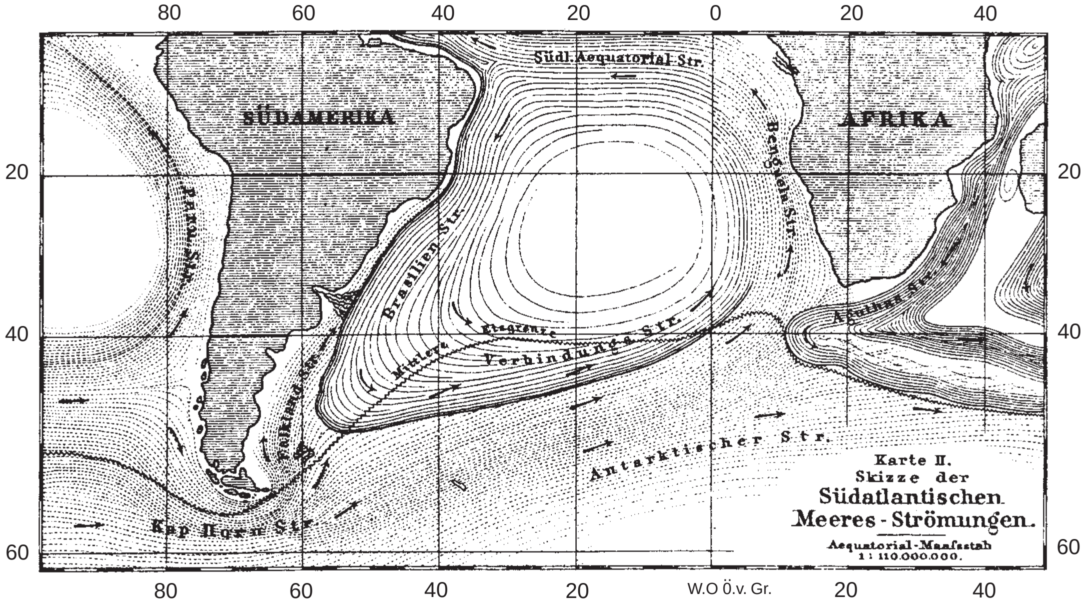

Figure 2 Chart of surface currents in the South Atlantic Ocean by Krümmel (1882).

meets the Scotia Ridge with increased speed, and shifts sharply northward. In subpolar and polar regions density variations with depth are small and the pressure gradient force is more evenly distributed over the water column than in the tropical and subtropical regions. As a result, the currents in the subpolar and polar regions extend to great depth. In the case of the subpolar gyre of the North Atlantic, the currents have a strong barotropic component (with little vertical velocity shear) and hence tend to follow f/h contours.

Historical Developments

Charts of ocean currents from the late nineteenth century show that by then the patterns of surface circulation in regions away from the equator and polar latitudes were already well understood. This fundamental knowledge accumulated gradually through centuries of sea travel and had reached a state of near correctness by the time dedicated research cruises, full depth measurements, and the practical application of the dynamical method were begun.

By the fifth century AD, mariners had probably acquired intimate knowledge of coastal currents in the Mediterranean, but little information about them is reported in Classical writing. Following the dark and Middle Ages when little progress was made, the voyages of discovery brought startling observations of many of the Atlantic's most important ocean currents, such as the North and South Equatorial Currents, the Gulf Stream, the Agulhas Current, and others. The Gulf Stream appears to have been mapped as early as 1525 (by Ribeiro) on the basis of Spanish pilot charts. The fifteenth to seventeenth centuries were marked by attainments of knowledge that increasingly taxed the abilities of science writers to reconcile new information with accepted doctrine.

Significant advances in determining the global ocean circulation beyond local mapping of currents came only after the routine determination of longitude at sea was instituted. The introduction of the marine chronometer in the late eighteenth century made this possible. Largely because of the marine chronometer, a wealth of unprecedentedly accurate information about zonal, as well as meridional, surface currents began to accumulate in various hydrographic offices. In the early nineteenth century data from the Atlantic were collected and reduced in a systematic fashion (by James Rennell), to produce the first detailed description of the major circulation patterns at the surface for the entire mid- and low-latitude Atlantic, along with evidence for cross-equatorial flow. This work provided a foundation for the assemblage of a global data set (by Humboldt and Berghaus) that yielded worldwide charts of the nonpolar currents by the late 1830s. Heuristic and often incorrect theories of what causes the circulation in the atmosphere and oceans were popularized in the 1850s and 1860s and led to a precipitous decline in the quality of charts intended for the public (Maury; Gareis and Becker).

However, errors in popular theories provided motivation for the adoption of analytical methods, which in turn led directly to the discovery of the full effect of Earth's rotation on relatively large-scale motion and the realization of how that effect produces flow perpendicular to horizontal pressure gradients (Ferrel). The precedents for modern dedicated research cruises came in the 1870s (e.g. the *Challenger* cruise), as well as mounting evidence for the existence of a deep and global thermohaline circulation (Carpenter, Prestwich). With the ever-increasing numbers of observations made at and near the surface, the upper-layer circulation in non-polar latitudes was approximately described by the late 1880s. A current map by Krümmel (1887) nicely described the surface currents of the entire Atlantic. This figure is not reproducible; however, **Figure 2** shows as an example an earlier and slightly less accurate map from Krümmel (1882), but only for the South Atlantic Ocean.

Currents of the Atlantic Ocean Warmwatersphere

The warmwatersphere, consisting of the warmer upper waters of the ocean, is the most climatologically important part of the ocean due to its direct interaction with the atmosphere. The transition from the warm- to the cold-watersphere takes place in a relatively thin layer at temperatures between 8° and 10°C. The warmwatersphere reaches to 500–1000 m depth in the Atlantic's subtropics and rapidly rises towards the ocean surface poleward of about 40° latitude.

The near-surface circulation is driven primarily by the wind and forced into closed circulation cells by the continental boundaries. The circulation of the Atlantic is governed by the subtropical gyres of the North and South Atlantic (**Figure 3**). The subtropical gyre of the North Atlantic includes the Florida Current and Gulf Stream as western boundary currents, the North Atlantic Current, the Azores and Canary Currents in the eastern Atlantic, the North Equatorial Current, and the Caribbean, Cayman and Loop Current in the Caribbean and Gulf of Mexico. The subtropical gyre of the South Atlantic includes the poleward-directed Brazil Current as western boundary current, which turns eastward at the Brazil/Falkland (Malvinas) confluence region as eastward flow near 40°S named South Atlantic Current. The South Atlantic Current in part continues to the Indian Ocean and in part adds to water from the Agulhas retroflection to the northward-flowing Benguela Current and the westward-flowing South Equatorial Current. Near the coast of north Brazil the South Equatorial Current contributes in part to the Brazil Current, but in part also to the subsurface intensified North Brazil Undercurrent, responsible for the warm water flow from the Southern to the Northern Hemisphere. The two anticyclonic subtropical gyres, clockwise in the Northern and counterclockwise in the Southern Hemisphere, reach through the entire warmwatersphere and show only weak seasonal changes. Subtropical gyres, although existing longitudinally to basin-scale, also tend to have sub-basin-scale recirculation gyres in their western reaches (**Figure 3**). The northward extent of the South Atlantic subtropical gyre decreases with increasing depth. It is located near Brazil at 16°S in the near-surface layer and at 26°S in the layer of Antarctic Intermediate Water.

The preferential north–south orientation of the continents bounding the Atlantic Ocean lead to meridional eastern and western boundary currents which together with the wind-induced zonal currents, westward flow under the trade winds, and eastward flow under the midlatitude westerly winds, form the closed gyres. The western ocean boundary regions are associated with an intensification of the currents. The consequent energetic western boundary currents, the Florida Current and the Gulf Stream in the North Atlantic Ocean and the Brazil Current in the South Atlantic Ocean, have large transports and typical width scales of ~100 km. The western boundary currents are intensified because the strength of the Coriolis effect varies with latitude. The western boundary currents of the Atlantic Ocean are generally so deep that they are constrained against the continental shelf edge and do not reach the shore (*see* **Brazil and Falklands (Malvinas) Currents** and **Florida Current, Gulf Stream and Labrador Current**).

In the Tropics the two subtropical gyres are connected via a complicated tropical circulation system. The tropical circulation shows a north-westward cross-equatorial flow at the western boundary and several zonal current and countercurrent bands (**Figure 4**) of smaller meridional and vertical extent and a lot of vertical diversification. The north-westward flow along the western boundary starts as a subsurface flow, the North Brazil Undercurrent, which becomes surface intensified north of the north-eastern tip of Brazil by near-surface inflow from the South Equatorial Current and is named North Brazil Current. The North Brazil Current crosses the equator north-westwards and retroflects eastward at about 8°N. In this North Brazil Current retroflection zone, eddies detach from the current and progress north-westward towards the Carib-

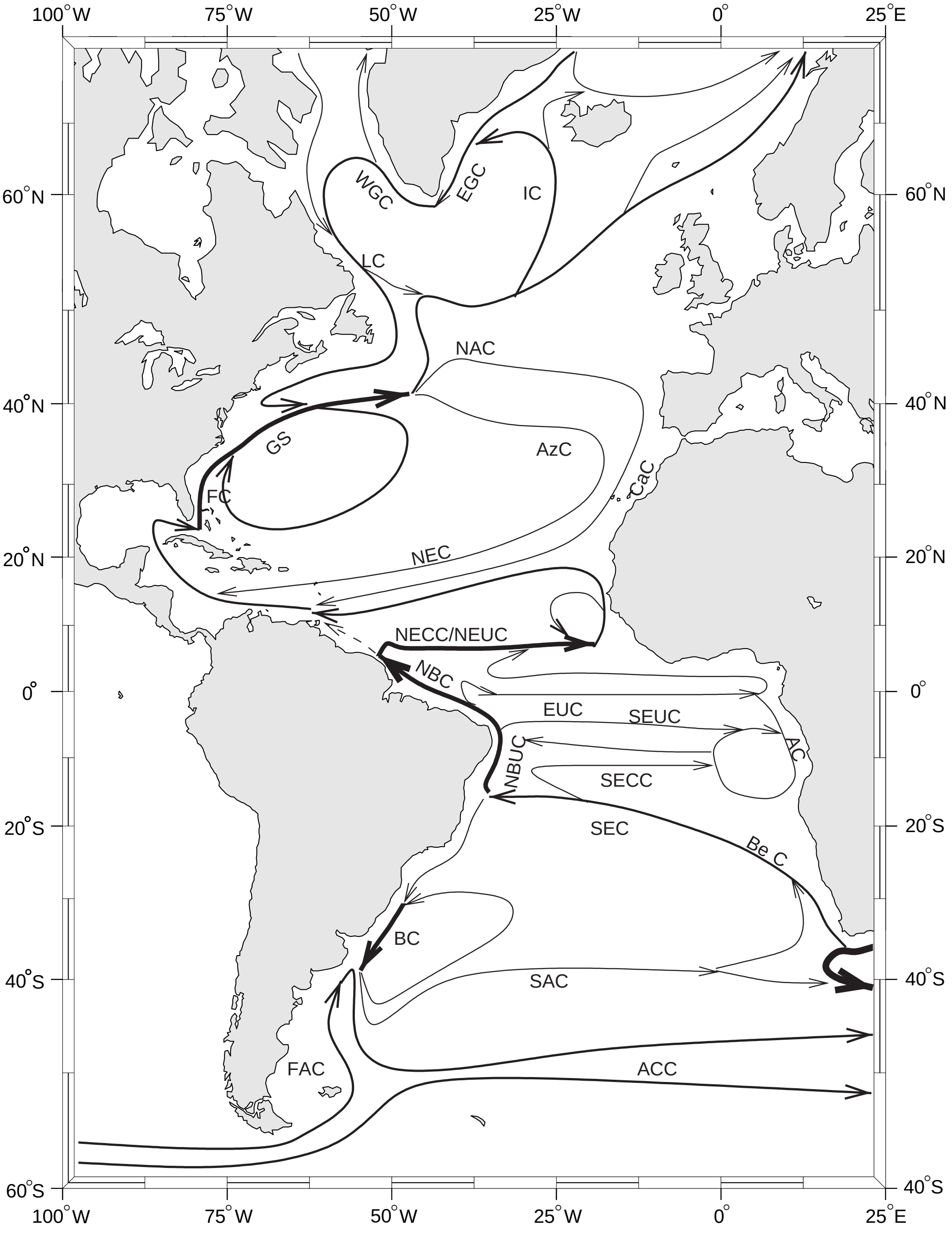

Figure 3 Schematic representation of upper-ocean currents in the North and South Atlantic Oceans in northern fall. For abbreviations of current bands see **Table 1**.

bean. In northern spring, when the North Equatorial Countercurrent is weak, there seems to be a continuous flow of about 10 Sv towards the Caribbean called Guyana Current. The westward flows are regarded as different bands of the South Equatorial Current, the northern one even crossing the equator. The eastward subsurface flows are named the Equatorial Undercurrent at the equator, and the North and South Equatorial Undercurrents at about 5° latitude. The eastward surface intensified flows at about 9° latitude are the North and South Equatorial Countercurrents. In northern fall the North Equatorial Countercurrent and the North Equatorial Undercurrent override one another and it is difficult to distinguish between the two current bands. In the Antarctic Intermediate Water layer at about 700 m depth there are intermediate currents at the equator (Equatorial Intermediate Current), as well as north and south of the equator (Northern and Southern Intermediate Countercurrents) which flow in the opposite direction to the currents above (**Figure 4**). The Intertropical Convergence Zone in the Atlantic, where the trade winds of both hemispheres converge, is located north of the equator throughout the year, and reaches the South Atlantic only in southern summer and then only at the north coast of Brazil. Seasonal changes of the wind field lead obvious variations in the tropical near-surface currents; however, with different strengths. The strongest seasonal signal is observed in the North Equatorial Countercurrent. The eastward-flowing North Equatorial Countercurrent is strongest in August, when the Intertropical Convergence Zone is located at its northernmost position. At that time the North Equatorial Countercurrent crosses the entire Atlantic basins zonally, but in late boreal winter it becomes weak or even reverses to westward in the western domain. South of the Cape Verde Islands at 9°N, 25°W, there is a cyclonic feature named Guinea Dome throughout the year, but it is weaker in northern winter. The Southern Hemispheric counterpart is the Angola Dome at 10°S 9°E. The Angola Dome is seen only in southern summer and it is imbedded in a permanent larger-scale cyclonic feature centered near 13°S, 5°E called Angola Gyre.

The western tropical Atlantic is a region of special interest in the global ocean circulation. The meridional heat transport across the equator is accomplished by warm surface water, central water, and subpolar intermediate water from the Southern Hemisphere moving northward in the upper 900 m mainly in the North Brazil Current, and cold North Atlantic Deep Water (NADW) moving southward between 1200 m and 4000 m. These reversed and compensating water spreading paths are often referred to as part of the global thermohaline conveyor belt. A clear distinction has to be made between the cross-equatorial flow at the western boundary and the interhemispheric water mass exchange. The latter is the amount of transfer from the Southern to the Northern Hemisphere of about 17 Sv in the upper ocean, and to a small degree in the Antarctic Bottom Water, compensated by the transfer from the Northern to the Southern Hemisphere of about 17 Sv by the North Atlantic Deep Water. The cross-equatorial flow within the North Brazil Cur-

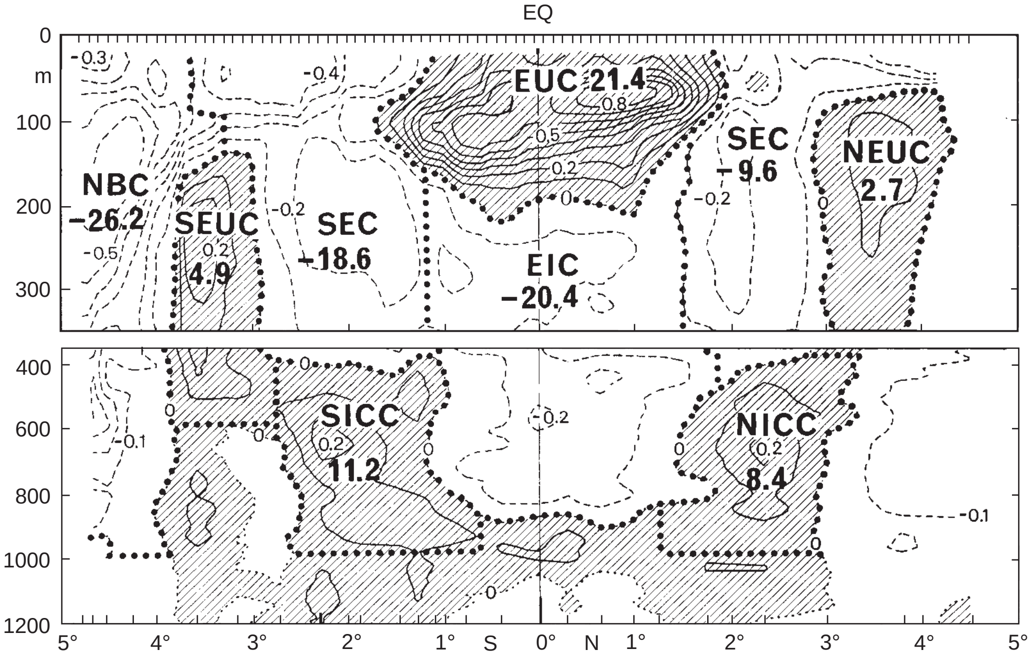

Figure 4 Zonal velocity component in m s^{-1} (eastward flow is shaded) from direct velocity measurements (ADCP) across the equator at 35°W in March 1994 north of the north-eastern tip of Brazil. Current branches are indicated and transport numbers are given in Sv. The figure shows the North Brazil Current (NBC), the South Equatorial Undercurrent (SEUC), the South Equatorial Current (SEC) with branches north and south of the equator separated by the Equatorial Undercurrent (EUC), the North Equatorial Undercurrent (NEUC), the Equatorial Intermediate Current (EIC), the Northern Intermediate Countercurrent (NICC), and the Southern Intermediate Countercurrent (SICC).

rent with about 35 Sv (**Table 1**) is much larger, since part of this cross-equatorial flow originates from the zonal equatorial circulation, retroflects north of the equator, and returns into the equatorial circulation system.

Poleward of the subtropical gyre the current field of the North and South Atlantic are completely different. In the North Atlantic a cyclonic subpolar gyre is present, driven in part by the wind stress curl associated with the atmospheric Icelandic low pressure system and in part by the fresh water from the subarctic. This subpolar gyre includes the northern part of the North Atlantic Current, the Irminger Current, the East and West Greenland Currents and the Labrador Current off north-eastern North America. In the South Atlantic the continents terminate and an eastward flow of water all around the globe within the Antarctic Circumpolar Current is driven mainly by the midlatitudes westerlies. The South Atlantic counterpart of the Labrador Current is the Falkland (Malvinas) Current, which flows equatorward along the south-eastern South American shelf edge to about 38°S. However, this current differs in origin as it is essentially a meander of a branch of the Antarctic Circumpolar Current. In the Brazil/Falkland (Malvinas) confluence region the Falkland (Malvinas) Current is retroflected southward to join the Antarctic Circumpolar Current. The South Atlantic Current as southern current band of the South Atlantic subtropical gyre and the Antarctic Circumpolar Current can be distinguished as separate current bands, nevertheless mass and heat exchange between the subtropics and subpolar region takes place in this region.

The currents of the North Atlantic subpolar gyre have a strong barotropic flow component, which lead to large water mass transports (**Table 1**). As the major method of estimating transport is by geostrophy, which provides only the baroclinic component, early transport estimates for this region with strong barotropic flow fields largely underestimated the real transports. Another prominent example is the Falkland (Malvinas) Current in the South Atlantic, where estimates including the barotropic component lead to transports of up to 70 Sv, while earlier geostrophic computations resulted in transports of about 10 Sv. Differences between transports presented in **Table 1** and transport values presented elsewhere might also arise from the location where the transport is estimated, as the mass transport changes along the flow path, or from different definitions of the boundaries of the current bands. For example, the Gulf Stream is measured to the deepest depth reached by the northward flow, while the southward-flowing Brazil Current is typically estimated only for the transport in the warmwatersphere, while the southward flow underneath is estimated separately as Deep Western Boundary Current.

Table 1 Major upper-ocean currents of the Atlantic Ocean and transport in Sv (1 Sv = $10^6\,m^3\,s^{-1}$)

Current name	*Abbreviation in **Figure 3***	*Transport in Sv*
Subpolar gyre		
East Greenland Current	EGC	40–45
West Greenland Current	WGC	40–45
Irminger Current	IC	16
Labrador Current	LC	40–45
North Atlantic subtropical gyre		
Gulf Stream	GS	90–130
North Atlantic Current	NAC	35
Azores Current	AzC	12
Canary Current	CaC	5
North Equatorial Current	NEC	20
Florida Current	FC	32
Equatorial currents		
North Equatorial Countercurrent	NECC	40
North Equatorial Undercurrent	NEUC	19 (mean)
Equatorial Undercurrent	EUC	20–30
North Brazil Current	NBC	35
North Brazil Undercurrent	NBUC	25
South Equatorial Undercurrent	SEUC	5–23
Angola Current	AC	5
South Equatorial Countercurrent	SECC	7
South Atlantic subtropical gyre		
Brazil Current	BC	5–22
South Atlantic Current	SAC	15–30
Benguela Current	BeC	25
South Equatorial Current	SEC	20 (southern band)
Southern South Atlantic		
Falkland (Malvinas) Current	FAC	up to 70
Antarctic Circumpolar Current	ACC	110–150

Currents of the Deep Atlantic Ocean

The deep-ocean circulation depends heavily on the changes in density imposed by air–sea interaction. The flow in the deep ocean is driven by the equator-to-pole differences in ocean density. This thermohaline circulation, driven by temperature and salinity gradients, provides global-scale transport of heat and salt. The forcing of this flow is concentrated in a few areas of intense production of dense water in the far North Atlantic, the Labrador Sea, and along the margin of Antarctica within so-called convection areas.

The water formed at the Antarctic continent is the densest water mass in the Atlantic and, once it has crossed the Antarctic Circumpolar Current (ACC), spreads as Antarctic Bottom Water through the South Atlantic western basins northward into the North Atlantic (**Figure 5**), where it can usually be found near the seafloor even north of 40°N. Actually, the real Antarctic water masses are so dense that they can be followed only to about 4.5°S, and Lower Circumpolar Deep Water spreads to the Northern Hemisphere. However, for historical reasons the name Antarctic Bottom Water is used generally for this water mass and is used here for consistency. In the north, Antarctic Bottom Water is

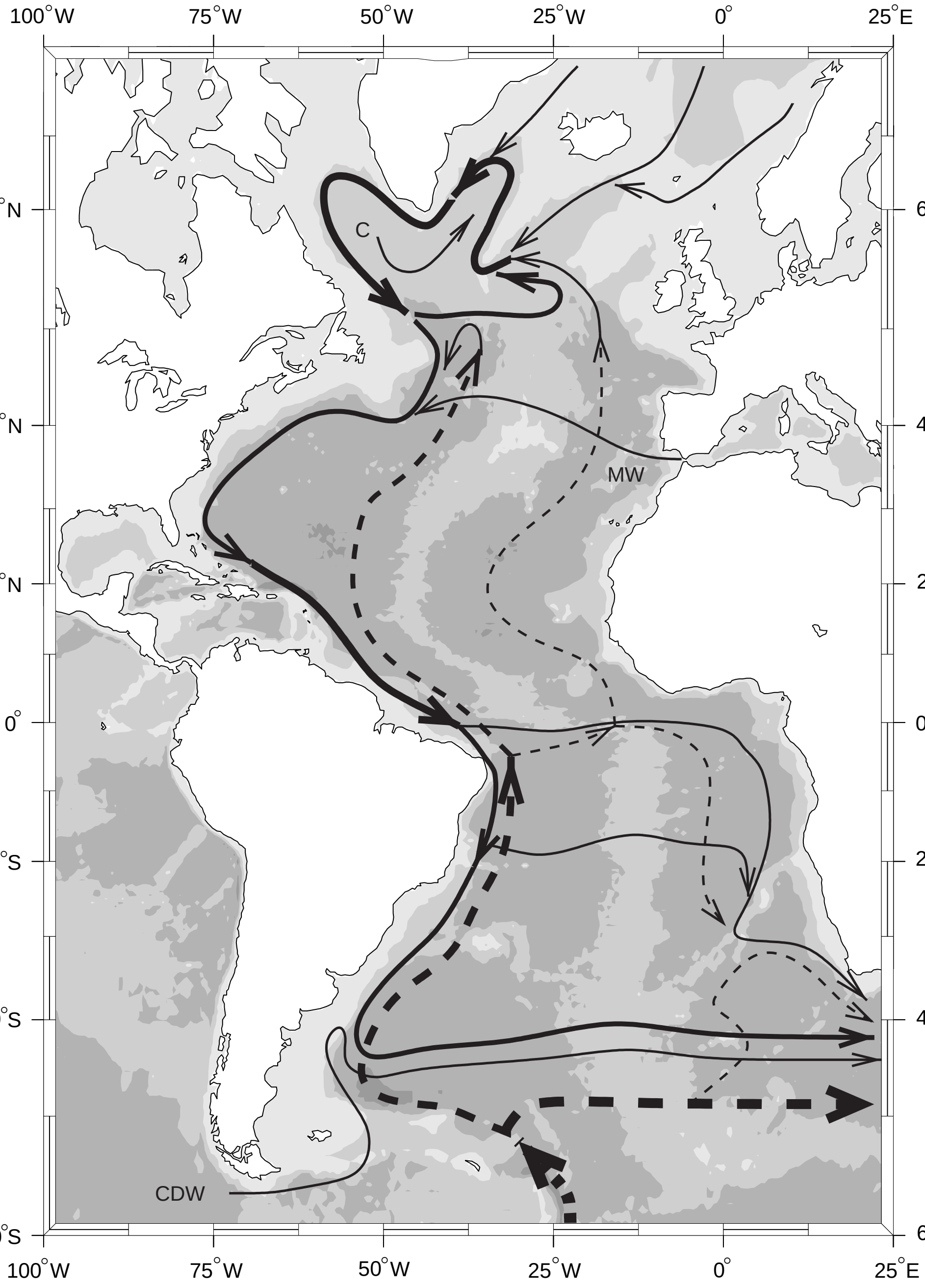

Figure 5 Schematic representation of the large-scale North Atlantic Deep Water flow (solid lines), Circumpolar Deep Water (CDW), and Antarctic Bottom Water (dashed lines). C denotes the convection region in the Labrador Sea, MW the entrance of Mediterranean Water to the North Atlantic. For readability of the figure no recirculation cells are drawn. Bottom topography in 2000 m steps.

modified by mixing and contributes to the North Atlantic deep water formation. The deep water of the North Atlantic (NADW) is composed of different sources in the northern Atlantic. The source for the deepest NADW layer is dense water from the Greenland Sea which overflows the Denmark Strait and is called Denmark Strait Overflow Water or lower NADW. South of the Denmark Strait the lower NADW entrains surrounding water, which in part contains modified Antarctic Bottom Water. The middle layer of NADW is a combination of overflow across the Iceland–Scotland Ridge with a light component of modified Antarctic Bottom Water. The upper layer of the NADW is caused by open-ocean convection in the Labrador Sea and is called Labrador Sea Water or upper NADW. A closer investigation of the Labrador Sea Water shows that it has two different sources. Mediterranean Water entering over the Strait of Gibraltar spreads westward in the North Atlantic and contributes saline water mainly to the upper NADW.

The NADW is trapped for some years within the deep-reaching North Atlantic subpolar gyre before it enters the Deep Western Boundary Current. Then the NADW spreads southward as Deep Western Boundary Current in the western ocean basins with recirculation cells to the east. When the NADW crosses the equator towards the South Atlantic part of the NADW flows eastward along the equator and then southward within the eastern basins. However, the major portion of the NADW continues to flow southward at the Brazilian continental margin as Deep Western Boundary Current. When the NADW reaches the latitude of the ACC the NADW is modified by mixing as it is carried eastward with the ACC around the Antarctic continent. Branches of the modified NADW, now often referred to as Circumpolar Deep Water, move northward again into the Indian and Pacific Oceans.

Future Aspects

Ocean research is always influenced by political and economic interests. The improvement in understanding of the surface currents at the time of the voyages of discovery was caused by the need for good and safe sailing routes. The more detailed look at the currents of the surface as well as the deep Atlantic were influenced by the interest in the resources of the sea for food, and the search for economic sources. The research focus on ocean currents in the Atlantic Ocean at the beginning of the new millennium will be improvement in understanding the mean surface and deep currents of the Atlantic, and its variability on short-term to decadal timescales to clarify the ocean's role in climate changes. These investigations are driven by the need to protect and manage the environment and the living conditions of all countries and are managed in large international research programs.

To improve the climate prediction models it is necessary to understand the ocean's role in climate changes better. International programs like Climate Variability and Predictability (CLIVAR) started to describe and understand the physical processes responsible for climate and predictability on seasonal, interannual, decadal, and centennial timescales, through the collection and analysis of observations and the development and application of models of the coupled climate system.

Another new important focus will be to describe and understand the interactive physical, chemical, and biological processes that regulate the total Earth system. This is also the overall objective of the International Geosphere-Biosphere Program (IGBP). One core project of IGBP is GLOBEC, which is now changing from a planning to a research status with the goal of advancing understanding of the structure and functioning of the global ocean ecosystem, its major subsystems, and its response to physical forcing so that a capability can be developed to forecast the responses of the marine ecosystem to global change.

Despite the future focus on the Atlantic's role in climate changes as well as interactive processes, and although the major components of the near-surface circulation from ship drift observations have been known for more than 100 years, there is still also the need to investigate details of the Atlantic Ocean subsurface and abyssal circulation and its physical processes, which so far are unrevealed.

See also

Abyssal Currents. Atlantic Ocean Equatorial Currents. Baltic Sea Circulation. Benguela Current. Brazil and Falklands (Malvinas) Currents. Canary and Portugal Currents. Current Systems in the Mediterranean Sea. Current Systems in the Southern Ocean. Florida Current, Gulf Stream and Labrador Current. Intra-Americas Sea. North Sea Circulation. Ocean Circulation.

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CURRENT SYSTEMS IN THE INDIAN OCEAN

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Introduction

The Indian Ocean is the smallest of all the oceans and is in several respects quite different from the others. In particular, it is bounded by the Asian continent to the north. This meridional land–sea contrast has a strong influence on the winds, resulting in a complete seasonal reversal of the winds known as the monsoon system. The characteristics of the basin and of the wind regime are determinant for the currents, and will be described first in this article. The description of the currents has been separated into two main sections: the first for the southern part of the Indian Ocean which is not affected by the monsoons and is more akin to the other subtropical oceans; and the second for the northern part which undergoes forcing through the reversal of the monsoon winds. Some information on the deep circulation and a short conclusion are then provided.

Characteristics of the Indian Ocean Basin

The Indian Ocean basin is the smallest of the five great subdivisions of the world ocean with $49.10^6\,\mathrm{km}^2$ out of the $361.10^6\,\mathrm{km}^2$ of the global ocean (**Figure 1**). It is closed to the north around the latitude of the Tropic of Cancer by the Asian continent, which has important consequences on the ocean circulation. South of the equator, its western boundary is modified by the presence of the island of Madagascar. In the east, the basin is connected with the equatorial Pacific Ocean through the deep passages of the Indonesian Seas. The north of the Indian Ocean is made up of the large basins on either side of the Indian peninsula, the Arabian Sea in the west and the Bay of Bengal in the east which drains most of the river runoff from the Himalayas and the Indian subcontinent. The Arabian Sea is connected directly to the shallow Persian Gulf, and through the sill of Bab-el-Mandeb (110 m) to the deep Red Sea basin where high salinity waters are formed. In the south, the basin is largely open to the Antarctic Ocean between South Africa and Australia. The Indian Ocean limit to the south is the Subtropical Convergence, a hydrological limit where the meridional surface temperature gradient is maximum. At depth, the complicated system of ridges separates the Indian Ocean in many deep basins (**Figure 1**).

The Overlying Atmosphere

Due to the presence of the Asiatic continent to the north, the atmospheric circulation is quite different from the Pacific Ocean and the Atlantic Ocean, particularly north of 10°S. Seasonal heating and cooling of the atmosphere over Asia induces a seasonally varying monsoon circulation (**Figure 2**). For centuries it has been known that the winds north of around 10°S reverse with the seasons. A long time ago the Arabic traders along the east African coast made use of the fair currents and winds during their voyages. The word ‘monsoon’ comes from the Arabic word ‘mawsin’ meaning season. As the winds are the main driver of the currents, in particular near the surface, the main characteristics of the wind seasonal variability will be described below.

The wind seasonal variability over the ocean can be separated in four periods: the winter monsoon period, the summer monsoon period, and the two transition periods between the two monsoons.

Between December and March–April, north of the equator, the winter (NE) monsoon blows from the north east with a moderate strength. At the