ATLANTIC OCEAN EQUATORIAL CURRENTS

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Introduction

The circulations of the tropical Atlantic and Pacific Oceans have much in common because similar trade winds, with similar seasonal fluctuations, prevail over both oceans. The salient features of these circulations are alternating bands of eastward- and westward-flowing currents in the surface layers (see **Figure 1**). Fluctuations of the currents in the two oceans have similarities not only on seasonal but even on interannual timescales; the Atlantic has a phenomenon that is the counterpart of El Niño in the Pacific. The two oceans also have significant differences. The Atlantic, but not the Pacific, has a net transport of heat from the southern into the northern hemisphere, mainly because of an intense, cross-equatorial coastal current in the Atlantic, the North Brazil Current. The similarities and differences between the tropical Atlantic and Pacific (and also the Indian Ocean) are of enormous interest to modelers because they provide invaluable checks on the theories and models that explain and simulate oceanic currents. Those currents play a central role in the Earth's climate, by influencing sea surface temperature patterns for example.

Time-averaged Currents

Although the trade winds that prevail over the tropical Atlantic Ocean have a westward component, the currents driven by those winds include the eastward North Equatorial Countercurrent, between the latitudes 3° and 10°N approximately. Sverdrup, in one of the early triumphs of dynamical oceanography, first pointed out that this current is attributable to the curl of the wind. Flanking this eastward current are westward currents to its north, the North Equatorial Current, and to its south, the South Equatorial Current. The latter current is particularly intense at the equator, where it can attain speeds in excess of $1\,\mathrm{m\,s^{-1}}$. **Figure 1**, a schematic map of the various currents, actually depicts conditions between July and September when the southeast trades are particularly intense and penetrate into the northern hemisphere.

Centered on the equator, and below the westward surface flow, is an intense eastward jet known as the Equatorial Undercurrent which amounts to a narrow ribbon that precisely marks the location of the equator. The undercurrent attains speeds on the order of $1\,\mathrm{m\,s^{-1}}$ has a half-width of approximately 100 km; its core, in the thermocline, is at a depth of approximately 100 m in the west, and shoals towards the east. The current exists because the westward trade winds, in addition to driving divergent westward surface flow (upwelling is most intense at the equator), also maintain an eastward pressure force by piling up the warm surface waters in the western side of the ocean basin. That pressure force is associated with equatorward flow in the thermocline because of the Coriolis force. At the equator, where the Coriolis force vanishes, the pressure force is the source of momentum for the eastward Equatorial Undercurrent which, in a downstream direction, continually loses water because of intense equatorial upwelling which sustains the divergent, poleward Ekman flow in the surface layers.

Along the African coast, cold equatorward coastal currents, the Canary Current off north-west Africa, and the Benguela Current off south-west Africa, are driven by the components of the winds parallel to the coast. These currents, which are associated with intense coastal upwelling and low sea surface temperatures, feed the westward North and South Equatorial Currents respectively.

Along the coast of South America, the most prominent current is the North Brazil Current, which carries very warm water from about 5°N across the equator. Some of that water feeds the Equatorial Undercurrent, but much of it continues into the northern hemisphere. Further south along the coast of Brazil, the flow is southward.

The net north–south circulation associated with the various currents is a northward flow of warm surface waters, and a southward return flow of cold water at depth, resulting in a transport of heat from the southern into the northern Atlantic. The southward flow below the thermocline is part of the global thermohaline circulation, which involves the sinking of cold, saline waters in the northern Atlantic. The absence of such formation of deep water in the northern Pacific – that ocean is less saline than the northern Atlantic – is part of the reason why there is a northward transport of heat across the equator in the Atlantic but not the Pacific.

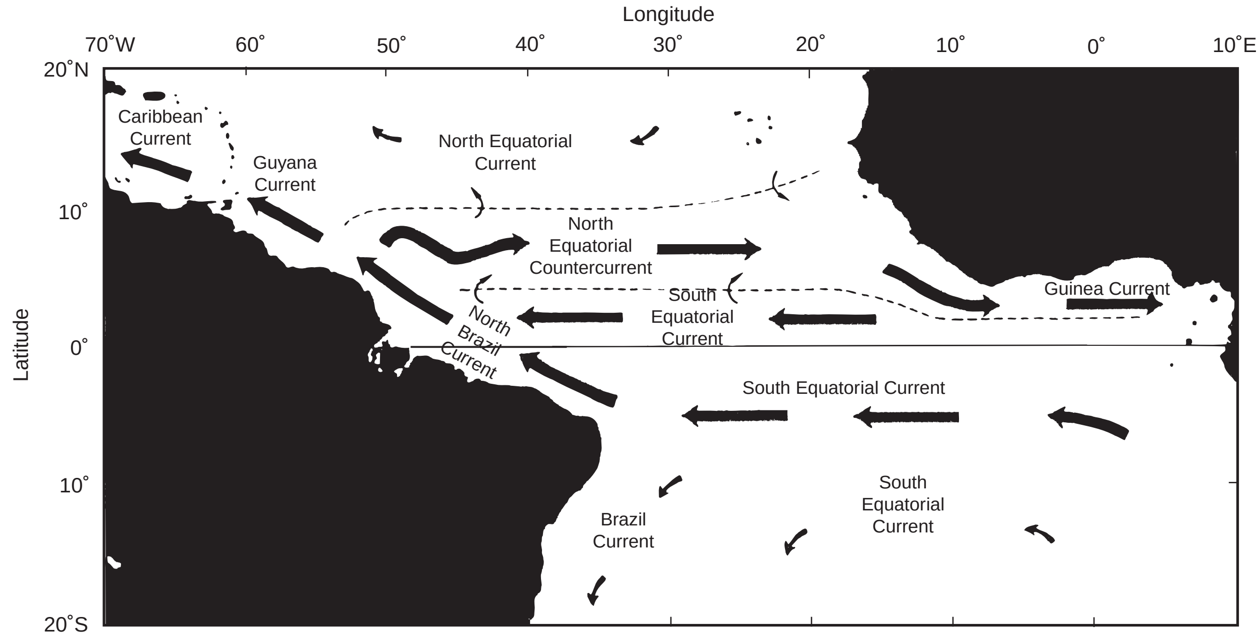

Figure 1 Schematic map showing the major surface currents of the tropical Atlantic Ocean between July and September when the North Equatorial Countercurrent flows eastward into the Guinea Current in the Gulf of Guinea. From January to May the North Equatorial Countercurrent disappears and the surface flow is westward everywhere in the western tropical Atlantic.

Seasonal Variations of the Currents

The seasonal variations of the winds are associated with the north–south movements of the Intertropical Convergence Zone (ITCZ), the band of cloudiness and heavy rains where the south-east and north-east trades meet. The south-east trades are most intense and penetrate into the northern hemisphere during the northern summer when the ITCZ is between 10° and 15°N. During those months the surface currents are particularly strong. The North Brazil Current, after crossing the equator, veers sharply eastward to feed the North Equatorial Countercurrent. The Equatorial Undercurrent is also strongest during this season when the east–west slope of the equatorial thermocline is at a maximum.

During the summer of the southern hemisphere, the zone where the north-east and south-east trades meet (the ITCZ) shifts equatorward so that the winds are relaxed along the equator. The North Brazil Current no longer veers offshore after crossing the equator, but continues to flow along the coast into the Gulf of Mexico. It is fed by surface flow that is westward at practically all latitudes in the tropics because, during this season, the eastward North Equatorial Countercurrent disappears from the surface layers, as is evident in **Figure 2**. At this time, the northward heat transport across 10°N is huge – on the order of a peta-watt; during the northern summer it is practically zero.

The upwelling along the west African coast, and the coastal currents too, are subject to large seasonal fluctuations in response to the variations in the local winds. Thus upwelling is most intense off south-western Africa, and surface temperatures there are at a minimum, during the late northern summer when the local alongshore winds are most intense. Off north-western Africa the season for such conditions is the late northern winter. The northern coast of the Gulf of Guinea (along 5°N approximately) also has seasonal upwelling, with lowest temperatures during the northern summer, even though the local winds along that coast have almost no seasonal cycle. In that region, changes in the depth of the thermocline (which separates warm surface waters from the cold water at depth) depend on winds everywhere in the equatorial Atlantic, even the winds off Brazil which are most intense during the northern summer when they cause a shoaling of the thermocline throughout the Gulf of Guinea.

If the winds over the ocean were suddenly to stop blowing, how long would it be before the currents in **Figure 1** disappear? The answer to this question (which is the same as asking how long it would take for the currents to be generated from a state of rest) is of central importance in climate studies because, associated with the currents, are sea surface temperature patterns that profoundly affect climate. (From a strictly atmospheric perspective, the cause of El

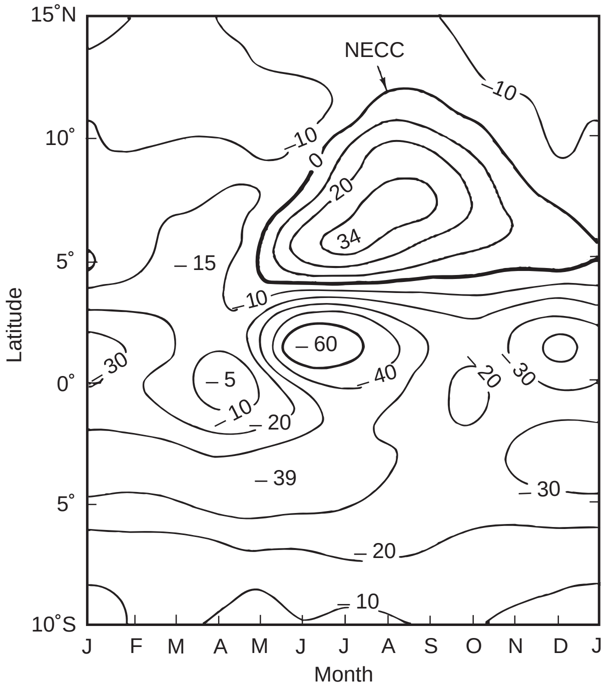

Figure 2 The seasonal disappearance of the North Equatorial Countercurrent (NECC) from the western tropical Atlantic. The eastward velocity in $\mathrm{cm\,s^{-1}}$ (negative values correspond to westward flow) is shown as a function of latitude and month, starting in January. The data, which have been averaged over a band of longitudes in the western equatorial Atlantic from 23°W to 33°W, are from shipdrift records.

Niño is a change in the surface temperature pattern of the tropical Pacific.) The Indian Ocean is ideal for studying these matters because there the abrupt onset of the south-west monsoons in May quickly generates the intense Somali Current along the eastern coast of Africa. Theoretical studies indicate that the generation of such currents, and more generally the adjustment of the ocean to a change in the winds, depend critically on waves (known as Rossby waves) that propagate across the ocean basin along the thermocline. The speed of those waves increases with decreasing latitude, reaching a maximum at the equator, which serves as a guide for the fastest waves – there they travel westward at about $50\,\mathrm{cm\,s^{-1}}$. The equator is also a guide for a very rapid eastward traveling wave, a Kelvin wave with a speed on the order of $150\,\mathrm{cm\,s^{-1}}$. The Somali Current near the equator can therefore be generated far more rapidly than can the Gulf Stream in mid-latitudes. The time it takes for the ocean to adjust (for the currents to be generated) depends not only on the speed of certain oceanic waves, but also on the width of the ocean basin. Hence it takes longer to generate the Kuroshio Current in the very wide Pacific, than the Gulf Stream in the smaller Atlantic.

If the winds change gradually rather than abruptly, then the timescale of the gradual changes relative to the time it takes the ocean to adjust determines the nature of the oceanic response. Thus winds that fluctuate on a timescale much longer than the adjustment time of the ocean will force an equilibrium response in which the ocean, at any given time, is in equilibrium with the winds at that time. (The currents and winds fluctuate essentially in phase.) From results such as these it can be inferred that the seasonally varying trade winds over the tropical Atlantic and Pacific Oceans should force an equilibrium response near the equator in the case of the small ocean basin, the Atlantic, but not in the case of the much larger Pacific. The measurements confirm this theoretical result: the seasonal variations of the currents and of the thermocline slope are in phase with the variations of the winds in the equatorial Atlantic, but not in the equatorial Pacific.

Interannual Variations

Given the similarities between the climates of the tropical Atlantic and Pacific – arid, cool conditions on the eastern sides, along the shores of Peru and south-western Africa, and warm moist conditions on the western sides – it should come as no surprise that the climate fluctuation known as El Niño has an Atlantic counterpart. As in the Pacific, such events involve a relaxation of the trades so that the warm waters that are usually confined to the western side of the basin flow eastward, causing a rise in sea surface temperatures off the south-west African coast where rainfall can increase significantly. To attribute this phenomenon to a relaxation of the trades is of course an oceanographic perspective. From a meteorological point of view, the warming of the eastern tropical Atlantic is the reason for the weakening of the winds and for several other changes in atmospheric conditions. This circular argument – changes in sea surface temperature are both the cause and consequence of changes in the winds – implies that interactions between the ocean and atmosphere are at the heart of the matter. Those interactions give rise to a variety of natural modes of oscillation which, in the Pacific, appear to be neutrally stable so that random atmospheric disturbances are able to sustain a continual oscillation, the Southern Oscillation, with a distinctive timescale on the order of 4 years. In the Atlantic the possible natural modes appear to be strongly damped and hence are far more sporadic than in the Pacific; there is no distinctive timescale for interannual fluctuations in the Atlantic. The main reason for this difference is the modest dimensions of the Atlantic relative to those of the Pacific. Some of the natural modes attributable to ocean–atmosphere interactions depend on the delayed response of the ocean to changes in the winds. If that delay is small, that is the case in an ocean basin of modest size – then the natural modes tend to be damped. Another factor that can inhibit interannual fluctuations is a particularly strong seasonal cycle. That cycle has a larger amplitude in the equatorial Atlantic than Pacific, because the influence of continents on the seasonal changes in the winds can exceed those of ocean–atmosphere interactions in a basin of small dimensions.

For a damped mode of oscillation to appear, a suitable perturbation is necessary. The occurrence of El Niño in the Pacific provides such a perturbation in the Atlantic by causing an intensification of the trade winds, and unusually low surface temperatures, in the Atlantic. (This is the impact of the presence of deep atmospheric convection over the eastern tropical Pacific during El Niño.) Apparently El Niño in the Pacific can amount to a preconditioning of the Atlantic because, on several occasions, El Niño in the Pacific was followed a year later by a similar phenomenon in the Atlantic. The amplitude of El Niño is generally much larger in the Pacific than Atlantic – the reason why the Pacific but not the Atlantic phenomenon is capable of a global impact.

El Niño, in the Atlantic and Pacific, has a structure that is essentially symmetrical about the equator. The Atlantic has an additional climate fluctuation that is anti-symmetrical relative to the equator, with sea surface temperatures that are high on one side of that line, low on the other side. The cross-equatorial winds then blow towards the warm side with exceptional intensity. If the higher temperatures are to the north, then the zonal band of heavy rains, the ITCZ, persists in a northerly position, bringing drought to north-eastern Brazil, and good rains to the Sahel, the region to the south of the Sahara desert in west Africa. The reverse happens when the ocean temperatures are high south of the equator, cool to the north.

Stability of the Currents

During the northern summer, the currents in the western equatorial Atlantic are so intense that they become unstable. One important factor is the enormous latitudinal shear between the eastward North Equatorial Countercurrent and the adjacent westward South Equatorial Current. The instabilities result in meanders that drift westward at a speed near $50\,cm\,s^{-1}$, that have a wavelength on the order of a 1000 km, and a period of approximately 1 month. The unstable conditions are confined to the western equatorial region where there is room for two or three waves at most – they sometimes appear in satellite photographs of sea surface temperature. The waves persist for a few months at most so that approximately three oscillations appear during the summer. The counterparts of these unstable waves in the eastern equatorial Pacific have a shorter period (close to 3 weeks) than in the Atlantic, cover a much larger region, and persist far longer. In the Pacific it is possible to observe very long wave trains – they can extend from the Galapagos Islands in the east to the dateline – that persist for many months.

See also

Brazil and Falklands (Malvinas) Currents. Coastal Trapped Waves. Current Systems in the Atlantic Ocean. El Niño Southern Oscillation (ENSO). El Niño Southern Oscillation (ENSO) Models. Florida Current, Gulf Stream and Labrador Current. Rossby Waves. Satellite Remote Sensing of Sea Surface Temperatures.

Further Reading

The *Journal of Geophysical Research* Volume 103 (1998) is devoted to a series of excellent and detailed review articles on tropical ocean–atmosphere interactions, including an article on oceanic currents.

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