The Oceanography Report

The Equatorial Undercurrent: 100 Years of Discovery

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The Equatorial Undercurrent is a narrow ribbon of eastward flow centered on the equator in the upper thermocline. It is a permanent feature of the general circulation in the Atlantic and Pacific oceans and is present in the Indian Ocean in northern winter and spring during the northeast monsoon. It reaches speeds of 50–100 cm s⁻¹ at more than 50 cm s⁻¹ at each of the three equatorial stations. Temperature measurements taken from the Buccaneer at 14°W (see cover) show a weakening of the thermocline within 2° of the equator, a feature now commonly associated with equatorial upwelling and enhanced vertical mixing in the undercurrent. On a later cable-laying cruise from

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J. Y. Buchanan and the First Measurements

John Young Buchanan (Figure 1) was born in Scotland of wealthy parents in 1844. His early education was in Glasgow, and he later attended universities in Germany and Paris to pursue a career in chemistry. On obtaining his degree, he returned to Scotland as an instructor at the University of Edinburgh, though he quickly discovered that he had no taste for teaching. Wyville Thomson was also at Edinburgh at this time, and through him Buchanan learned about the Challenger Expedition, which Thomson was helping to organize. Buchanan was eager to join the expedition, and his reputation for hard work and resourcefulness ultimately won him an appointment to the Challenger's scientific staff.

The Challenger Expedition lasted from December 7, 1872 to May 24, 1876, during which time 362 deep sea stations were occupied with the ambitious goal of investigating “the physical and biological conditions of the great ocean basins” [Thomson, 1878a]. Through his participation in the Challenger Expedition, Buchanan made several important contributions to the nascent science of oceanography. For example, he was the first to describe the oxygen minimum in at intermediate depths around 600 m (although he incorrectly interpreted it as being caused by an abundance of animal life [Thomson, 1878b]). He also published a series of papers on the specific gravity of sea water, from which he inferred the distribution of salinity [Buchanan, 1877, 1884]. Turbation had not been perfected yet, so Buchanan relied on hydrometer determinations of specific gravity and tables for conversion to a constant temperature of 15.56°C (60°F). His charts and vertical sections showed the global distribution of surface salinity for the first time and revealed such features as Antarctic intermediate water penetrating into the North Atlantic. He also observed and commented on an isolated subsurface salinity maximum in the Atlantic equatorial thermocline associated with the as yet undiscovered undercurrent.

Buchanan made many other scientific contributions, including work on the chemical composition of newly discovered manganese nodules [Buchanan, 1891]. He also demonstrated that increasing pressure enhanced the solubility of calcareous planktonic skeletal debris raining down from the euphotic zone, which explained why the deeper parts of the ocean floor were covered with red clays rather than Globigerina ooze. He likewise put to rest the theory that the sea floor was extensively blanketed with “Bathybius Haeckelii” or as it was alternately known, Urschleim [Buchanan, 1876]. This was an invention of Thomas Huxley, who, on inspecting deep sea calcareous sediments preserved in alcohol, noted the presence of a quivering, jellylike substance that he believed to be primordial protoplasmic ooze. He argued that all higher organisms evolved from this substance and named it after Ernst Haeckel, who was a leading proponent of the theory of spontaneous generation. While on board the Challenger, Buchanan showed the substance to be a precipitate of calcium sulfate and completely devoid of life. Huxley, faced with Buchanan’s irrefutable analysis, immediately and frankly recanted. Ironically, many of Huxley’s disciples were slower to follow suit, being unwilling to accept the fallibility of the great naturalist.

Following the Challenger Expedition, Buchanan continued his researches as he had begun at sea. He was, however, a man “with little tendency for friendship” [Deacon, 1971], and at one point he so rankled the British Trea-
cause the Arctic and Antarctic were the last great unexplored expanses of the globe in the late 19th century. Support for this research was motivated more by political rather than scientific considerations, however, since it was a matter of national pride to be first in the race to the poles. Buchanan was rather unsympathetic to this expedient form of pursuing research and remarked that "the warm and pleasant waters of tropical oceans are still almost untouched and teem with objects of interest, and in their exploration and investigation there are no difficulties to overcome, discomforts to be endured or dangers to be faced." Logistically, however, the tropics were too remote, and there was less compelling commercial, political, or military benefit in studying them.

Aside from these political stumbling blocks, Buchanan failed to generate widespread enthusiasm for his discovery because he was a loner and not much of an organizer. More fundamentally, however, the undercurrent did not stimulate any serious scientific inquiry since the dynamics of ocean circulation were so poorly understood at this time. The debate over whether the ocean was driven primarily by winds or by density differences had been raging since before the Challenger Expedition but was for the most part argued by geologists and biologists with limited training in mathematics or physics. For example, the importance of the earth's rotation and the motive force resulting from a sea level slope of $10^{-6}$ were not fully appreciated. Moreover, the Challenger Expedition did not help to resolve basic theoretical issues as had been anticipated. Only two of the 50 volumes of the Challenger report (one of which contained contributions by Buchanan) dealt with the physical and chemical properties of seawater.

Buchanan remained an advocate of tropical

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Senegalese to the island of Fernando Noronha, he again observed the undercurrent in the western Atlantic and noted [Buchanan, 1896a] that "there is every reason to believe that it is a constant and important factor of the oceanic circulation."

Buchanan [1886] argued that "the study of the currents of equatorial regions would well repay the trouble of the investigation," although he understood that systematic study of the equatorial current system would require more than occasional observations from sporadic cable survey cruises. In the wake of what many politicians considered to be the extravagance of the Challenger Expedition, however, the British government had become very tightfisted when it came to support of basic research. Funds were available only for a limited range of practical problems in physical oceanography, such as those in support of North Sea fisheries research. Opportunities were also developing in polar science be-
Buchanan, although he did not concentrate his efforts there. He pursued a diverse range of interests, encompassing such topics as the sperm whale and its food (Buchanan, 1896) and submarine geology (Buchanan, 1927). His accomplishments were many by the time he died in 1925, but his colleague Hugh Mill wrote "Had Buchanan been a poor man, or one bound to some permanent scientific position, he would probably cut a deeper niche for himself." Moreover, in enumerating Buchanan's contributions to science, Mill did not mention the undercurrent, which by this time had been all but forgotten.

Rediscovery in the 20th Century

The Equatorial Undercurrent was rediscovered in the tropical Pacific by Townsend Cromwell and Ray Montgomery aboard the R/V Hugh M. Smith in 1952. Oceanography had undergone a significant intellectual, technical, and organizational evolution since the late 19th century, so that these new measurements had a dramatically different impact on oceanography than Buchanan's did. In particular, an infrastructure has been established in the United States to promote basic oceanographic research after the Second World War. This infrastructure consisted of numerous private and government laboratories engaged in oceanographic research, funding agencies such as the newly instituted National Science Foundation, and an expanded community of oceanographers resulting from the demands of war research in the previous decade. Also of relevance were mechanization and other technical advances in the fishing industry that led to the development of an open ocean tropical tuna fishery.

Thus the U.S. Fish and Wildlife Service began a series of semiannual hydrographic cruises in January 1950 to aid in fisheries development. These cruises, originating from the service's Pacific Oceanic Fisheries Investigations (POFI) Laboratory in Honolulu, Hawaii, were to define the physical, chemical, and biological environment of the central equatorial Pacific and to survey fish resources there. The survey was to be conducted by using longline fishing gear, which consisted of miles of cotton line to which were attached floats and baited hooks. The line would sink to depths of 50–250 m depending on placement of the floats and vertical shear of prevailing currents.

Townsend Cromwell was chief scientist aboard several of these cruises and noted that near the equator the longline system often drifted upwind against the surface flow, at times reaching speeds of 50 cm s⁻¹. Large wire angles were also encountered within 2° of the equator during hydrographic casts, suggesting the existence of strong vertical shears. The significance of these observations was not fully appreciated, however, as Cromwell began organizing a cruise in early 1952 to make direct measurements of currents near the equator using drogued buoys. He was primarily interested in studying the meridional circulation that controlled upwelling and near-surface nutrient concentrations, since these were a central focus of POFI programs (e.g., Cromwell, 1955).

Montgomery became involved in the later stages of planning this cruise as part of a summer visitors program recently instituted by POFI. Cromwell was the only physical oceanographer in Hawaii at that time and had limited interaction with the larger community on the mainland. The visitors program was designed to remedy this, and Montgomery, a professor at Brown University (Providence, R.I.), was the first to accept an invitation. Dick Stroup, a support scientist at POFI, assisted in the planning and preparations for the cruise (including the design of the drogues) and later collaborated in the analysis of the data.

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There are two ironies associated with this publication. The first is that the method of...
measuring current velocity with drogues was not new at all but had been used by Buchan to measure the Atlantic Undercurrent and by others before him in the 19th century. Second, the editors of the journal were adamant in insisting that the article emphasize the measurement technique and not the discovery of the undercurrent, since they deemed the former to be more interesting.

The definitive cruise report was published by Montgomery and Stommel [1962] 10 years after the original measurements. The delay was in part because Cromwell left the Fisheries Service in Honolulu to work for the Inter-American Tropical Tuna Commission in San Diego, Calif. Montgomery, on the other hand, moved to Johns Hopkins University (Baltimore, Md.), and Dick Stroup remained in Honolulu for several years before joining Montgomery to pursue graduate studies. The publication was also delayed because Cromwell withdrew from authorship to concentrate on fronts research and later died in an airplane crash near Guadalajara, Mexico, in 1958 [Knauss, 1960]. However, the 1954 article and conference reports were sufficient to stimulate the oceanographic community so that the "Cromwell Current," as it was sometimes referred to after his death, became a subject of intense study by the late 1950s.

New Data, Old Data, and Theories

The Equatorial Undercurrent generated so much excitement because it was a "new" discovery that had not been predicted by recent theories of the general circulation [Sverdrup, 1947; Stommel, 1948; Munk, 1950]. These theories had successfully accounted for the existence of major ocean currents such as the Gulf Stream and Kuroshio and explained the western intensification of wind-driven gyres in terms of the sphericity of the earth. The theories were for depth-integrated flow, however, and so the existence of the undercurrent was obscured. Furthermore, incorporation of vertical structure near the equator was not straightforward because the Coriolis force, an important component of these theories, vanished at the equator. This led to singularities both in the surface Ekman layer and in deep geostrophic flows so that the undercurrent could not be easily reconciled with prevailing views of the general circulation.

Unraveling the dynamics of the Equatorial Undercurrent would require a more comprehensive data set than that provided by a single cruise of the Hugh M. Smith. Thus, during the International Geophysical Year (IGY, 1957–1958) and afterwards into the 1960s, the United States, France, Japan, and the Soviet Union launched expeditions in the Pacific to determine the meridional, vertical, and zonal extent of the undercurrent and its relation to temperature, salinity, and chemical tracer distributions. The description that emerged from these expeditions and the dynamical insights that they provided are summarized in Figures 3 and 4. Figure 3 shows the undercurrent in the central Pacific between 2°N and 2°S in the upper thermocline. Core speeds exceed 100 cm s⁻¹ and eastward transport is ~40 × 10⁶ m³ s⁻¹. The South Equatorial Current flows above the undercurrent and separates it from the surface countercurrents to the north and south.

The spreading of the thermocline seen in Figure 3 is consistent with a cross-stream geostrophic balance of zonal velocity and results from a vigorous meridional circulation and intense vertical mixing. (This figure should be compared with Buchanan's temperature section, on the cover.) The meridional circulation is induced by easterly trade winds, which produce poleward surface Ekman flows of the order of 10 cm s⁻¹ near the equator. This Ekman divergence is fed by upwelling at a rate of about 1 m per day, which brings cold nutrient-rich, oxygen-poor water to the surface and distends the upper thermocline. Upwelling is in turn maintained by a geostrophic convergence in the thermocline, with meridional currents of the order of 1 cm s⁻¹ balanced by an eastward pressure gradient force at depth. This geostrophic convergence is indirectly indicated by the tongues of high and low salinity directed towards the equator in the upper few hundred meters.

Turbulent mixing is produced by intense vertical shear of the undercurrent both above and below its core. Turbulence tends to homogenize the thermal structure near the equator and so works in concert with the field of vertical velocity to weaken the thermocline. Turbulent vertical diffusion of zonal momentum is also the principal force returning flow of the undercurrent.

Figure 4 shows the variation in thermal structure and pressure along the equator. The trade winds pile up warm water in the western Pacific, creating a deep mixed layer and tilting the thermocline up toward the east. The excess of warm, low-density water in the west leads to sea level about 50 cm higher than in the east and an eastward pressure gradient force to about 250 m. A few degrees to the north and south this pressure gradient drives the convergent geostrophic mass flux toward the equator. At the equator, the deflecting force caused by the earth's rotation vanishes, and the undercurrent flows down gradient in the thermocline.

The Equatorial Undercurrent is generally present across the entire span of longitudes shown in Figure 4, shuffling from west to east in tandem with the thermocline. It is likewise present further to the west of 160°E, although it exhibits greater temporal variability there because of the monsoonal character of the wind field in the western Pacific. Conversely, the zonal pressure gradient reverses east of the Galapagos Islands, and the under-
current is shunted southward to feed the Peru Coastal Undercurrent.

The interpretation of these data was aided by theories that began to appear in the late 1930s (e.g., Stommel, 1960; Charney, 1960) (see Figure 5). These theories established the central role of westward winds in setting up a baroclinic zonal pressure gradient to provide the source of eastward momentum for the undercurrent. Moreover, this pressure gradient eliminates singularities in the Ekman layer and so allows for a reevaluation of the dynamic and Sverdrup dynamics. By using these theoretical concepts and historical data, Neumann (1960) discussed the similarities between Atlantic and Pacific wind regimes and sea level and predicted that an undercurrent would be found in the Atlantic. His work anticipated the first direct measurements by Soviet and U.S. expeditions, who found an Atlantic Undercurrent similar in all its essential aspects to that in the Pacific (Vogt, 1961; Metcalf et al., 1962).

The Soviet measurements were made aboard the R/V Mikhail Lomonosov; hence the undercurrent is sometimes referred to as the Lomonosov Current (Philander, 1973). Measurements in the Indian Ocean would prove to be more elusive. The Indian Ocean is dominated by seasonally reversing monsoons and mean westerly winds along the equator. Easterlies prevail only during the northeast monsoon, which lasts from approximately December to April. Researchers therefore expected that an undercurrent and eastward pressure gradient would be present in the thermocline only during the northern winter and spring. This was confirmed independently by Soviet, British, and U.S. scientists who found subsurface flow along the equator at speeds of 50–100 cm s⁻¹ during the International Indian Ocean Expedition (Knauss and Taft, 1964; Swallow, 1964). Furthermore, the zonal pressure gradient associated with this flow reversed during the southwest monsoon, at which time the undercurrent was either absent or poorly developed.

This flurry of measurements in the decade after Cromwell and Montgomery’s discovery was complemented by an analysis of historical data. This has already been cited (Neumann, 1960). In addition, Tsuzuya (1961) reviewed Japanese archives and discovered that the Japanese Navy made direct observations of the Equatorial Undercurrent between 183°E and 166°E in the 1920s and 1930s. These measurements, made with Ekman current meters, were neither properly interpreted nor widely publicized and so fell into obscurity. However, they clearly showed an eastward undercurrent flowing at speeds of 50–100 cm s⁻¹ in the deep western Pacific thermocline.

Buchanan’s work came to light at this time as well. Montgomery and Stroup (1962) and Montgomery (1962) found reference to the Equatorial Undercurrent in historical records of the eastern equatorial Pacific and the relation of current fluctuations to the El Niño/Southern Oscillation phenomenon. The Tropic Heat project began a systematic study of the processes that control equatorial sea surface temperature variability and the role of the undercurrent in mediating those processes. These and other field programs, as well as a reexamination of theoretical issues (e.g., Mcreary, 1980; McPhaden, 1981) and the development of numerical models of the equatorial Pacific, led to renewed interest in the undercurrent, as reflected in the increased number of publications into the 1980s. (The percentage index rises less steeply because oceanography itself had grown over the same time period.)

Perhaps the most dramatic observations of Equatorial Undercurrent variability in recent years were made during the 1982–1983 El Niño. The trade winds reversed over much of the western and central equatorial Pacific in late 1982, which led to a collapse of the zonal pressure gradient (Cane, 1983). Direct velocity measurements indicated the virtual disappearance of the undercurrent from September 1982 until January 1983 at 150°W (Firing et al., 1983) and during January and February 1983 at 110°W (Halpern, 1983). Equatorial upwelling ceased as a consequence of these radical wind, current, and pressure changes, causing major disruptions in primary productivity (Barber and Chaves, 1983) and in global cycling of carbon dioxide (Gammon et al., 1986). Cessation of upwelling also led to basin-scale equatorial sea surface temperature anomalies of −3°C. These were associated with intense atmospheric convection that maintained the most pronounced El Niño of the century (Rasmusson and Wallace, 1983).

These observations signal a shift in undercurrent research that could be viewed as a transition from a basic theoretical description of its dynamics. Consequently, interest began to wane and was further diminished in the early 1970s as the oceanographic community geared up for the Mid-Ocean-Current Experiment (MODE), a study of mesoscale eddy variability at mid-latitudes. Philander (1973) published a review article in 1973 on theories and observations of the undercurrent that summarized most of what was known up to that time and that marked the close of the first phase of undercurrent exploration in the 20th century.

A second phase began in the mid-1970s as the undercurrent was studied as one component of large-scale field programs designed to address broader issues of tropical oceanography. One of the first of these programs was the GARP (Global Atmospheric Research Program) Atlantic Tropical Experiment (GATE), which was designed to examine air-sea interaction on atmospheric “weather” time scales. Data from this experiment drew attention to the fact that the undercurrent was not steady but instead meandered with a period of several weeks and a zonal wavelength of 2900 km (Ding et al., 1975). Later, programs such as the North Pacific Experiment (NORPAX) and the Indian Ocean Experiment (INDEX) focused on seasonal variability in equatorial current and hydrographic structures. Similarly, the Equatorial Pacific Ocean Climate Study (EPOCS) concentrated on interannual variability in the eastern equatorial Pacific and the relation of current fluctuations to the El Niño/Southern Oscillation phenomenon. The Tropic Heat project began a systematic study of the processes that control equatorial sea surface temperature variability and the role of the undercurrent in mediating those processes. These and other field programs, as well as a reexamination of theoretical issues (e.g., McCreary, 1980; McPhaden, 1981) and the development of numerical models of the equatorial Pacific, led to renewed interest in the undercurrent, as reflected in the increased number of publications into the 1980s. (The percentage index rises less steeply because...

### Meetings

**Deep Ocean Circulation and its Relation to Topography**

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A meeting to discuss the present state of knowledge concerning the deep circulation of the world ocean and to suggest priorities for research for the next decade was held at Woods Hole Oceanographic Institution, June 17–19, 1986 under the auspices of the U.S. Planning Office for the World Ocean Circulation Experiment (WOCE). This was one of five topical meetings sponsored in 1986 by the U.S. WOCE planning effort.

The meeting agenda was roughly divided into three subjects: circulation, bottom effects/dynamics, and measurement schemes and techniques. A unifying theme underlying much of the discussion concerned the applicability of the Stommel-Arons schematics for the deep circulation [Stommel and Arons, 1960a,b]. Some 30 years after their first publication, the ideas associated with the Stommel-Arons model have become the cornerstone of our understanding of the deep circulation, yet they have not been tested for much more than their semiquantitative predictions of deep western boundary currents. The nature of the forcing of the abyssal general circulation, its strength, its vertical structure, its time dependence, and its response to large-scale topography are logical areas for future study.

Specific recommendations for future research are as follows.

- The available information on deep boundary currents provides an incomplete picture of the paths and rates of deep flow in the world ocean. The data have been imparted by both additional hydrography in specific areas and time series measurements within the deep western boundary currents to quantify transports and their long-period variations.
- An attempt should be made to measure directly the deep interior flows and their vertical structure. Before a global exploration of such flows is started, a pilot experiment in an appropriate area should be conducted as soon as possible in order to guide more ambitious efforts that follow during WOCE.
- Because measurements of transports in passages provide strong constraints on the budgets of neighboring basins and are rela-