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# The seasonal transport of the Equatorial Undercurrent in the western Atlantic (during the Global Weather Experiment)

Equatorial Undercurrent
Mass transport
Atlantic Ocean
Seasonal variation
Global Weather Experiment

Sous-courant équatorial
Transport de masse
Océan Atlantique
Variation saisonnière
Première expérience mondiale du GARP

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ABSTRACT

Twenty-eight observations of the transport of the Atlantic Equatorial Undercurrent are reported from the Global Weather Experiment. The transport is computed relative to 500 m from meridional sections of profiling current meter stations. The majority of the sections are from the western Atlantic. A seasonal cycle of the transport in that region is inferred from the data and compared to models of the oceanic response to variable wind stress.

The average transport in the western Atlantic is $21 \times 10^6 \, m^3/sec.$ (within the 20 cm/sec. isotach and above 200 m). The maximum value was observed in March, $44 \times 10^6 \, m^3/sec.$, during light winds and it is related to the seasonal occurrence of large (one knot) eastward surface currents at the equator. A two month period of 25 % below average transport is identified beginning in late May. Minimum transport ($10 \times 10^6 \, m^3/sec.$) lags the minimum zonal wind stress by about 2 months.

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RÉSUMÉ

Transport saisonnier du sous-courant équatorial dans l'Atlantique Ouest (pendant l'expérience mondiale du GARP)

Vingt-huit observations du transport du sous-courant équatorial Atlantique ont été effectuées pendant l'expérience mondiale du GARP. La majorité provient de l'Atlantique Ouest. Un cycle saisonnier du transport dans cette région est estimé à partir de ces données et comparé aux résultats des modèles théoriques de réponse de l'océan aux variations de la tension du vent.

Le transport moyen dans l'Atlantique occidental est de $21 . 10^6 \, m^3/s$ (entre les contours de 20 cm/s et au-dessus de 200 m). La valeur maximale a été observée pendant le mois de mars : $44 . 10^6 \, m^3/s$ durant de faibles vents, et a été reliée à l'apparition saisonnière d'un fort courant de surface (un nœud) vers l'est, à l'équateur. Vers la fin du mois de mai, commence une période de 2 mois pendant laquelle le transport est de 25 % au-dessous de la moyenne. Le transport minimal ($10 . 10^6 \, m^3/s$) est décalé de 2 mois par rapport à la valeur minimale de la tension du vent local.

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## INTRODUCTION

The Equatorial Undercurrent of the Atlantic Ocean was introduced into modern scientific literature by Neumann (1960). Apparently unknown to him, an anchor station detecting the undercurrent had already been made by the Marine Hydrophysical Laboratory of the USSR in May, 1959 (Voigt, 1961) from the research vessel Mikhail Lomonosov. The first known attempt to make a current profiling section of the undercurrent followed in April, 1961 (Metcalf *et al.*, 1962) and showed its narrow meridional extent about the equator. Since then it has been observed and reported on by numerous investigators and the following description has evolved.

The current is an ever present eastward zonal flow, about 200 km wide and centered within 100 km of the equator, which flows counter to the usually prevailing trade winds. Though not always a subsurface flow, the maximum velocity is generally between 50 to 125 m deep, in the upper part of the thermocline. The undercurrent traverses the entire Atlantic. Metcalf and Stalcup (1967) describe its origin from the waters of the N. Brazilian Coastal Current flowing across the equator from the Southern Hemisphere, while Hisard and Morlière (1973) describe a variety of endings deep in the Gulf of Guinea. Upstream the waters being advected in the core of the undercurrent are anomalously saline, but the persistence of the anomaly downstream is seasonally variable, depending on the extent of vertical mixing (Katz *et al.*, 1979). The mean depths of the thermocline and the cores of the undercurrent and salinity anomaly monotonically decrease to the east. This shallowing of the thermocline results in an eastward pressure gradient in the upper 200 m of the ocean. The gradient is small, or may even reverse, in the Gulf of Guinea. It is also seasonal, weakening across the basin in the boreal spring (Katz *et al.*, 1977).

A range of maximum velocities and transports of the undercurrent have been reported. The former are generally between 60 and 130 cm/sec. Philander (1973) gave the latter as varying between 14 and $37 \times 10^6$ m$^3$/sec., and nothing very different has been reported since then.

It is difficult to compose a reliable picture of the seasonal behavior of the undercurrent from historical data because of incomplete reporting, unknown interannual and zonal differences, different reference levels, etc. Instead we will report below a completely new data set from the Global Weather Experiment which minimizes, if not eliminates, many of these problems. Once a seasonal pattern is recognized, we will return to the historical data for confirmation of specific details. The addition of a continuous wind record from the area will also permit us to relate our oceanic observations to the atmospheric forcing of that year (and not the climatological mean). This is important because theoretical models of equatorial dynamics are intrinsically synoptic.

Table
*Transport of the Equatorial Undercurrent (relative to 500 m).*

| Ship | Longitude (°W) | Date (mo/day/yr.) | No. of stations | Directly Computed Transport ($10^6$ m$^3$/sec.) | | From (3) and (4) | |
|---|---|---|---|---|---|---|---|
| | | | | | | Half width ($y_L$ n.m.) | Transport ($10^6$ m$^3$/sec.) |
| | | | | 0-200 m | 0-500 m | | 0-200 m |
| Besnard | 33 | 1/27/79 | 9 | 27.2 | 31.1 | 80 | 27.4 |
| | 28 | 2/5/79 | 7 | 15.6 | 16.2 | 60 | 16.2 |
| | 33 | 7/1/79 | 9 | 11.0 | 11.4 | 70 | 11.4 |
| | 28 | 7/10/79 | 9 | 15.2 | 17.6 | 70 | 16.2 |
| Capricorne | 4 | 8/6/78 | 4 | 4.9 | 4.9 | 20 | 4.5+ |
| | 4 | 4/5/79 | 6 | 11.8 | 12.2 | 40 | 12.1+ |
| Conrad | 33 | 10/9/79 | 9 | 20.0 | 20.3 | 70 | 20.7 |
| | 28 | 10/13/79 | 9 | 18.5 | 18.9 | 60 | 18.3 |
| | 33 | 10/21/79 | 9 | 17.4 | 17.8 | 45 | 17.6 |
| Discovery | 27.5 | 11/10/78 | 7 | – | – | 90 | 19.5 |
| | 32.5 | 11/14/78 | 7 | – | – | 75 | 20.7 |
| Oceanus | 28 | 3/4/80 | 9 | 41.4 | 48.8 | 85 | 43.5 |
| Researcher | 26 | 8/1/78 | 6 | – | – | 75 | 23.8 |
| | 25 | 8/3/78 | 6 | – | – | 85 | 25.9 |
| | 15 | 7/10/79 | 3 | – | – | 25 | 15.5+ |
| | 18 | 7/11/79 | 3 | – | – | 45 | 14.4+ |
| | 22 | 7/13/79 | 3 | – | – | 90 | 17.3+ |
| | 25 | 7/14/79 | 5 | 10.1 | 10.1 | 50 | 10.5 |
| | 25 | 2/24/80 | 4 | – | – | 45 | 23.2 |
| Suroit | 4 | 8/4/78 | 7 | 11.4 | 19.4 | 45 | 10.9+ |
| V. Humboldt | 28.7 | 5/9/79 | 7 | 25.4 | 25.4 | 80 | 26.1 |
| | 28.7 | 5/15/79 | 7 | 24.1 | 24.1 | 60 | 24.2 |
| | 28.7 | 5/18/79 | 7 | 21.7 | 22.0 | 65 | 22.0 |
| | 28.7 | 5/21/79 | 7 | 18.0 | 18.0 | 65 | 18.5 |
| | 28.7 | 5/24/79 | 7 | 15.9 | 15.9 | 60 | 16.3 |
| | 28.7 | 5/31/79 | 7 | 18.1 (*) | – | 60 | 18.3 (*) |
| | 28.7 | 6/2/79 | 5 | – | – | 65 | 21.6 (*) |
| | 28.7 | 6/13/79 | 5 | – | – | 50 | 13.7 (*) |

(*) Relative to 1000 m; +, excluded from averages.

## THE DATA

Between August 1978 and March 1980 oceanographers from six countries, exclusive of the USSR whose data are not included here, made more than 200 individual current profiles within 2° of the equator. Most of these lowerings were part of meridional sections across the equator and these are enumerated in the Table. In discussing the data we will collapse it and consider it as all coming from a single one-year period. While not strictly valid, long time wind records suggest that the intensification and weakening of equatorial winds occurs over time scales of several years (after removal of the seasonal cycle). If we can suppose that the ocean responds in a similar manner, then data from 2 consecutive years will have less interannual variability than data from many years. An analysis of the sea surface temperature in the tropical Atlantic (Weare, 1977) from 1911-1972 shows some support for this hypothesis.

The profiles are all from drifting ships which lowered different current meters to depths of 500-1 000 m. Thus, for comparative purposes, transport is given here as relative to 500 m (unless otherwise noted). From five sections where the data are available, currents relative to 1 000 m were computed. These sections have $4 \times 10^6$ m$^3$/sec. more transport on the average compared with a 500 m reference level. There was no intercalibration of current meters.

The transport, T, of the undercurrent is given by:

$$T = \iint u(y, z)\, dz\, dy, \qquad \text{or} \tag{1}$$

$$\cong \int t(y)\, dy \qquad \text{and} \qquad t \equiv \int u\, dz, \tag{2}$$

where $u$ is the zonal velocity component (re. 500 m); $z$ and $y$ are depth and meridional co-ordinates. The limit of the integration is taken as the area in which $u \geqq 20$ cm/sec.; where $t$ is the transport per unit width at a single station. The difference between (2) and (1) is demonstrably insignificant.

There are two difficulties in applying the above to the data set. Firstly, the zonal velocity at 500 m may vary across the sections (velocities of 10 cm/sec. are reported by various investigators from ship drift measurements and by Weisberg *et al.*, 1979). Limiting the integration to within the 20 cm/sec. isotach is the classical method of reducing the effect of this uncertainty on the calculation of transport (by not including large regions of uncertain eastward flow). We will also limit our later discussion to flow above 200 m for the same purpose. The second problem is that about one-third of the available sections do not extend far enough from the equator to include the entire undercurrent transport (usually 2°, sometimes 1°30′ is sufficient). In a couple of sections, station spacing is too coarse (separations of more than 30′ between 1°N to 1°S can make the integration questionable).

To make a "best estimate" of transport from the incomplete sections, we have fitted a Gaussian distribution to each section (an idea suggested by Eric

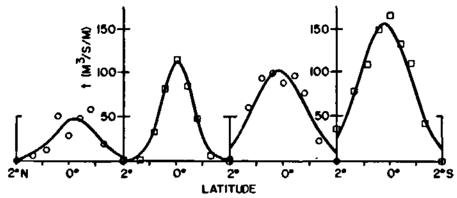


Figure 1

*Examples of a Gaussian fit to four sections. The transports are* 11, 18, 27 *and* 44 × 10⁶ *m³/sec. (from left to right).*

Firing's treatment of Pacific data, personal communication). The result for several representative sections is shown in Figure 1. Thus:

$$t(y) = t(y_0)\exp(-((y - y_0)/y_L)^2), \tag{3}$$

and, from (2):

$$T = (\pi)^{1/2}\, t(y_0)\, y_L, \tag{4}$$

where $y_L$ is the half-width of the transport and $y_0$ is its meridional center. $y_0$ is determined by finding the centroid of the observations and $y_L$ and $t$ are then determined simultaneously by minimizing the variance between the observed and estimated values of $t(y)$.

In the table are given both the transports obtained from the raw data (0-200 m, 0-500 m) and from (4). By a comparison of the appropriate columns it is seen that the transport (0-200 m) is essentially the same regardless of how it is computed.

An estimate of the error in computing transport from incomplete sections was made by assuming that profiles were available for only 1°N, 0° and 1°S from the eight Besnard, Conrad and Oceanus sections, and that $t = 0$ at 2°N and 2°S. On the average, the resulting transports agreed with the original estimates (from the complete sections) to within $0.3 \times 10^6$ m$^3$/sec. with a standard deviation of $1.7 \times 10^6$ m$^3$/sec.

Typical values of the transport of the undercurrent in the Gulf of Guinea are substantially lower than upstream. The few observations included in the table will not shed much light on its seasonal variation and we will exclude them from our later discussion. With regard to the three sections east of 25°W, but still in the central Atlantic, we do not know whether to include or exclude them. Katz *et al.* (1979) showed a gradual increase in transport from 33° to 16°W and then a sharp decrease at 10°W, but it would be unwise to generalize from a single observation. To be safe, we will also discount the small set of data east of 25°W in our discussion of seasonal variation.

## THE SEASONAL TRANSPORT

In Figure 2 we have plotted the undercurrent transport above 200 m in the western Atlantic during the composite year "1979" (last column in the table). Twenty-two values are shown between 25° and 33°W. The mean value of these measurements is $20.7 \times 10^6$ m$^3$/sec. with a standard deviation of 6.9 and a standard error of the

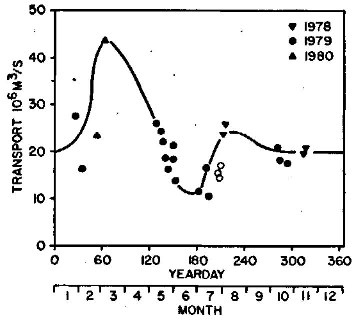


Figure 2

*Transport of the equatorial undercurrent between 25° W and 33° W during the Global Weather Experiment. Data are listed in the last column of the Table. Transport is relative to 500 m and limited to within the 20 cm/sec. eastward isotach above 200 m. Open circles are data from 15° W-22° W.*

mean of 1.5. We have however gone one step further and sketched a curve through the data describing what we will propose is a reasonable extrapolation of the data. It has two features, a large increase in transport during March and a definite minimum in June/July, which we support as follows:

The large increase in March was observed during only one section and was not observed 9 days earlier 180 n. m. to the east. It is important to note that the increased transport is primarily due to a reversal of the surface layer velocity rather than an acceleration of the undercurrent core. In Figure 3, we show four zonal current sections at 28°W observed between February 1979 through March 1980. The first three yield transports of 16-18 × $10^6$ $m^3$/sec., while the last gives the extreme value of 44 × $10^6$ $m^3$/sec. The difference between the latter and its predecessors is characterized by the strong eastward surface flow (above 60 cm/sec. at the equator) compared to either westward or less than 20 cm/sec. eastward flow. The core velocity of 120 cm/sec. is not unusual during the course of the year and occurs in sections with transports of only 25 × $10^6$ $m^3$/sec. The large transport in March is primarily due to the strong eastward surface current, a current twice as large as observed in any of the other twenty-two sections. In contrast, the section made at 25°W recorded a westward surface current of 54 cm/sec.

During the measurements at 28°W the winds were light and from the northeast (the ship was of course carried eastward while on station). This suggests that the section was made when the Intertropical Convergence Zone was south of the equator (at 2°S judging from when the wind direction changed to a southeast trade). A 1979 wind record from St. Peter and St. Paul rocks (0°55′N, 29°21′W) reveals a similar decrease in wind occurring during the previous year about the beginning of April (Fig. 4). In fact we know that this is a frequent, perhaps yearly, occurrence. The first reports of the "undercurrent" were actually of easterly surface currents of a knot or more under low wind conditions in March 1893 and 1894 (Neumann, 1960). Neumann also refers to the Atlantic Surface Current charts in 1940 which "calls attention to the abnormal set of ships in the region between 30 and 35°W just south of the equator, where eastward currents were observed from early December to the beginning of Mày". Ship drift relative to a reference buoy during Equalant I found surface speeds of 40-60 cm/sec. to the east of 35°W on 3-5 April 1963 (Stalcup, Parker, 1965). The wind was Beaufort force 1. Moored current meters at 30 m depth at 27°30′W, 30°W and 32°30′W indicate eastward currents between 0°30′S and 1°30′N from late February to mid-March 1963 (Stalcup, Metcalf, 1966). Thus we must conclude that a one knot eastward surface current along the equator is not unusual in the boreal spring. Resulting transports of the "surfaced" undercurrent will be correspondingly increased, as observed.

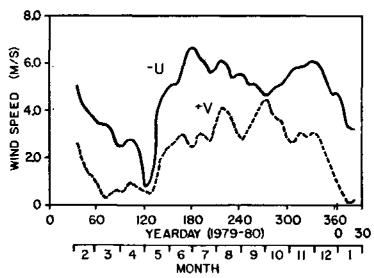


Figure 4

*Wind components from St. Peter and St. Paul rocks. Data recorded hourly (vector averaged). Smoothed with 21-day tapered filter. Averaged wind is always from the southeast.*

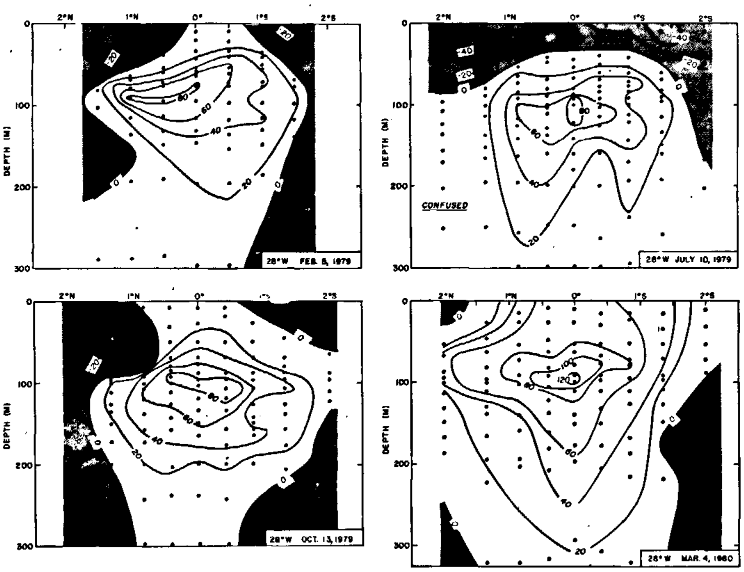


Figure 3

*Zonal current along 28° W on four occasions. Contours are in units of cm/sec. Eastward flow is unshaded.*

The second feature suggested by the dashed curve in Figure 2 is that the transport is below average from 20 May to 20 July. Seven of eight observations made in this period fall below the annual mean. The mean transport of the eight sections is 15.8 × $10^6$ $m^3$/sec. with a standard error of 1.3 (the three sections between 15 and 22°W also average 15.7 × $10^6$ $m^3$/sec.). Thus, after the maximum transport season follows a minimum transport period which is 25% less than the annual mean and has values as low as 11 × $10^6$ $m^3$/sec. That this occurs when the zonal wind stress is again relatively strong is attributed to a delayed response.

Support for the reduced transport of the undercurrent during the boreal summer comes from the GATE data. Düing and Hallock (1979) report values of 7.5-

$11.2 \times 10^6$ m$^3$/sec. (absolute) within the 20 cm/sec. isotach from eight repeated sections at 28°W between 31 July and 16 August 1974. Two even smaller values were reported for July 27 and 29th, but the core was displaced to a position near one end of the sections and the calculation may be incomplete. Katz *et al.* (1979) report 9.4 and $8.9 \times 10^6$ m$^3$/sec. from 28°W and 33°W in July 1974, but these are relative to 300 m. Transports computed from five current meters further to the east (23°30'W) are reported by Bubnov *et al.* (1976). Their average values for three 20-day intervals between 27 June and 18 September 1974 are 16.7, 10.7 and $14.9 \times 10^6$ m$^3$/sec. (above 200 m and between 1°30'N and 1°30'S). We conclude that in July/August 1974, as in May/July 1979, transports were well below $20 \times 10^6$ m$^3$/sec. Minimum transports of about $10 \times 10^6$ m$^3$/sec. were observed in both years.

## OCEANIC RESPONSE TIMES

Recent numerical models give both an estimate of the oceanic response times to changes in the wind stress as well as some details of the sequence in which the adjustment occurs. Of particular interest are studies by Cane (1979 and 1980) and Philander and Pacanowski (1980). The latter is a generalization of the Cane two-layer model which gives similar results and effectively justifies the assumptions implicit in the Cane model. Since the Cane model is somewhat simpler to describe, we will limit our discussion to it.

The two layers in the model are a surface layer of constant depth and a lower layer of variable depth above an ocean at rest. There is no density difference between the active layers, and mass and momentum are transferred across the boundary. The wind stress is felt directly only by the surface layer. Thus the upper layer simulates the wind driven layer of the ocean, and the second layer simulates the undercurrent region. The zonal pressure gradient is given by the change in thickness of the lower layer. The set-up time for a wind-driven circulation, starting from rest, is found to be several hundred days (150 days by Philander and Pacanowski) in a basin the size of the Atlantic. Though the model ocean is not quite in equilibrium with seasonally varying winds, most of the response to wind changes occurs on shorter time scales.

The model predicts two types of responses to changes in wind stress. The first response is "local" and is related to the direct wind forcing of the upper layer. The second response is "non-local" and is related to equatorial propagation of boundary generated waves which perturb the lower layer thickness. The initial response to a cessation of easterlies is local and immediate. The surface layers accelerate in response to the zonal pressure gradient which is as yet unperturbed. The total eastward transport along the equator increases accordingly. After about 10 days the non-local response begins to play a role: the zonal pressure gradient is reduced as Kelvin waves propagate in from the western boundary. The total eastward transport is diminished as a consequence of the reduced pressure gradient and, after 40 days, the transport of the lower layer is halved (Fig. 10; Cane, 1980).

The rapid return to relatively strong winds in May is modeled by imposing a constant westward wind on an ocean initially at rest. The eastward zonal pressure gradient is found to be strongly developed only 2-3 weeks after the initiation of the wind, for either linear or non-linear dynamics (Fig. 4 and 9; Cane, 1979). In 6 to 7 weeks the kinetic energy of both layers attain 90% of its equilibrium value in the equatorial band (Fig. 8; Cane, 1979, non-linear case). These responses are directly related to the time it takes a Kelvin wave excited at the western boundary to propagate across the basin and the time scales of westward propagating Rossby waves. The surface flow is now to the west.

The data sets on hand are not ideally suited for the purpose of inferring oceanic response times. The transport data are discontinuous, are from a band of longitudes, and overlap the preceding and following years. The wind data, while suitably located and presumably typical of a wider area, are from a single site. Nevertheless, a comparison with the above model predictions can be made as follows.

Maximum transport was observed in March 1980, about 3 months after the wind began to weaken. Shipboard observations noted that the winds were weak and from the NE at that time (the same condition occurred during several 3-day periods in March 1979 as well, but were averaged out in Fig. 4). The maximum response occurred in the upper layer of the ocean, where strong eastward flow was observed (Fig. 3). Minimum transport occurred about 2 months after the minimum zonal wind stress, or 4 months after the first instance of weak NE wind near the equator. Qualitatively, these results can be explained in terms of model results, a relatively quick local response in the upper layer followed by a longer term response in the lower layer.

The transport recovered in 1 or 2 months, after exposure to strong wind forcing. However, the transport was not as large as the earlier maximum because of the opposing direction of the surface flow. Again, the results are consistent with model results after easterly winds are turned on.

A more exacting comparison between model and data is not yet possible, but it appears that the model and the data are describing the same events in relatively the same time scales.

**Acknowledgements**

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