Zonal pressure gradient along the equatorial Atlantic

by Eli Joel Katz[1] and Collaborators[2]

ABSTRACT

For three consecutive periods during the summer of 1974, ships of many nations made observations along the Atlantic equator as part of the GATE program [GARP (Global Atmospheric Research Program) Atlantic Tropical Experiment]. Combining these observations, it is found that the zonal pressure gradient over the central Atlantic at the surface and at 50 dbar, relative to 500 dbar, increased from 3.2 to 7.3 and 2.2 to 5.3 $\times 10^{-5}$ dynes/g respectively between June/July and August and then held close to the high values in September. The latter depth, 50 dbars, approximates the depth of the undercurrent. A comparison with synoptic data from Equalant I (March/April, 1963), Equalant II (August/September, 1963) and *Crawford* Cruise No. 22 (November, 1958) suggests a seasonal trend of low values in the boreal spring to high values in mid-summer through fall in the western and central Atlantic. This trend is paralleled both by the zonal wind stress as observed simultaneously with the oceanographic measurements, and by the average annual cycle of the zonal wind stress on the equator. The wind stress attains a minimum value coincident with the southernmost displacement of the intertropical convergence zone.

1. Introduction

Since the recent discovery of the equatorial undercurrent in the Pacific, Atlantic[3], and Indian Oceans, its existence has been explained by the predominantly easterly winds along the equator. In theory, the zonal pressure gradient resulting from the wind field drives an eastward undercurrent beneath the generally westward, wind-driven, surface current whose characteristics are modified by a predicted meridional circulation (and by friction). Two comprehensive summaries of the observational record and the dynamic theories have been published recently (Philander, 1973; and Gill, 1975). They review both the consistency and the uncertainties of the observational record and the various attempts to proceed theoretically from the under-

1. Woods Hole Oceanographic Institution, Woods Hole, Massachusetts, 02543, U.S.A.

2. This work is the result of an ad hoc committee whose following members uniformly analyzed their original data: R. Belevitsch, State Oceanographic Institution, Odessa, U.S.S.R.; J. Bruce, Woods Hole Oceanographic Institution, U.S.A.; V. Bubnov, Institute of Oceanology, Kaliningrad, U.S.S.R.; J. Cochrane, Texas A&M University, U.S.A.; W. Düing, University of Miami, U.S.A.; P. Hisard, CRO ORSTOM, Abidjan, Ivory Coast; H.-U. Lass, Institut für Meereskunde, G.D.R.; J. Meincke, Institut für Meereskunde, F.D.R.; A. deMesquita, University of São Paulo, Brazil; L. Miller, University of Rhode Island, U.S.A.; A. Rybnikov, Oceanography Institution, Moscow, U.S.S.R.

3. In fact, re-discoveries of currents called the Cromwell Current in the Pacific and the Lomonosov Current in the Atlantic by some authors.

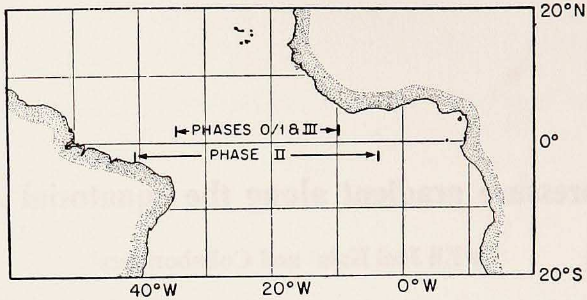

Figure 1. Zonal extent of observations at the equator during the three phases of GATE.

lying zonal pressure gradient driving force to a quasi-steady undercurrent which agrees with more than one manifestation of the observations.

The stimulus for discussing the zonal pressure gradient along the equatorial Atlantic Ocean at this time is a new set of quasi-synoptic observations which adds substantially to what has been available. They are reported here for the first time (§2) and then combined with previous synoptic observations in order to examine the variation of the pressure gradient (§3). Evidence for the correlation between wind stress and pressure gradient is presented (§4). Our present nearly complete inability to comment observationally on the response of the undercurrent in the Atlantic to variable forcing is duly noted (§5). Finally, for comparison, the zonal pressure gradient of the Pacific Ocean is discussed (§6) before summarizing the results (§7).

2. The GATE equatorial observation program

In the summer of 1974, an extensive international meteorological/oceanographical experiment (GATE) was carried out in the tropical Atlantic. A detailed description of all aspects of this experiment can be found in the series of GATE reports published by the World Meteorological Organization, International Council of Scientific Unions (Geneva). One element of this program resulted in twelve ships making oceanographic observations on the equator between 4°W and 42°W. The data from ten of these ships are reported here (Table 1 and Fig. 1). Three kinds of sampling programs are included. The first of these are time series measurements, generally at the equator. The second are sections, generally orthogonal to the equator. The third are a mixture in that specific stations on and near the equator were reoccupied numerous times in a sequential manner. The undercurrent, during the time of the measurements, was meandering meridionally about the equator in a manner identified as that of a westward travelling wave with a 16-day period (Düing *et al.*, 1975). Its core, defined by maximum zonal current, was apparently limited to the 1°N-1°S band. We have treated this variation in the current and density

Table 1. GATE Data Set.

Ship	Country	Dates (1974)	Longitude (°W)	No. of Stations	Data Code
Atlantis II	USA	13-14 VI	10	5	A
		17 VI	11.5	5	A
		17-18 VI	13	5	A
		19 VI	14.5	6	A
		21-23 VI	16	5	A
		28-29 VI	22	5	A
		10-11 VII	24	7	A
		15-17 VII	28	5	A
		19-20 VII	30	10	A
		22-23 VII	33	5	A
Capricorne	Ivory Coast	27 VII	4	5	A
		28-29 VII	7.25	5	B
		30 VII-10 VIII	10	21	C
Fay	USA	28-30 VII	40.75	5	D
		4 VIII	36	3	D
		12-13 VIII	38.25	5	D
V. Humboldt	GDR	28 VII-7 VIII	23.5	12	C
Iselin	USA	28 VII-6 VIII	28	16	C,E
Kurchatov	USSR	28 VI-16 VII	23.5	144	F
		28 VII-13 VIII	23.5	60	F
		3 IX-17 IX	23.5	98	F
Passat	USSR	27 VI-16 VII	10	120	F
		27 VII-15 VIII	10	152	F
		29 VIII-19 IX	10	136	F
Saldanha	BRAZIL	26 VI-16 VII	35	87	F
		1-17 VIII	38	84	G
		1-19 IX	35	126	G
Semen Dezhnev	USSR	3-4 VII	25.5	5	A
		10-11 VII	23.5	5	A
		3-4 VIII	25.5	5	A
		10-11 VIII	23.5	5	A
		5 IX	25.5	5	A
		11 IX	23.5	4	A
Trident	USA	15-21 VII	28	11	H
		4-14 VIII	28	43	I
		14-16 IX	28	12	A
Anton Dohrn	FDR	10-15 VIII	29	26	F

[A] Meridional sections between 1°N-1°S.
[B] Zonal section along equator between 5.5°W and 9°W.
[C] Five sites (1.5°N, .75°N, 0°, .75°S, 1.5°S) re-occupied.
[D] Oblique sections between 1°N-1°S.
[E] Four stations on 29°W—Twelve on 28°W.
[F] Time series on equator.
[G] Time series at 2°N.
[H] Like A but 2 sections averaged.
[I] Like A but 4 sections averaged.

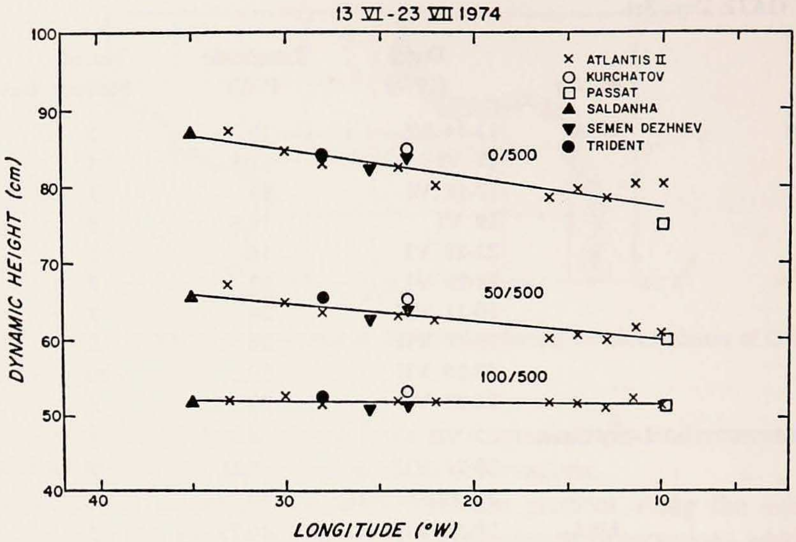

Figure 2. Dynamic height of the 0, 50, and 100 dbar surface relative to 500 during Phase O/I of GATE. Straight lines are the result of linearly regressing the height on longitude. For this figure and Figures 3 and 4, see Tables 1 and 2 for additional information.

field as a noise to the larger scale zonal pressure gradient and have attempted to average it out. Thus, the time series measurements were averaged over each of the three phases (approximately 3 weeks) of the experiment and meridional sections were averaged over the band of 1°N to 1°S and, where multiple sections were taken during a single phase, averaged again.

To include the largest representation of data possible without weakening the results, the 500 dbar surface was taken as the reference surface from which to compute the surface and near-surface dynamic heights. The 500 dbar relative to 1000 dbar surface was on the average 0.5 dyn cm (dynamic centimeters) higher to the west of 23°W than to the east (*Atlantis II* data) and the difference from month to month was on the average 1.0 dyn cm (*Kurchatov, Passat,* and *Saldanha* data).

All but one of the ships participated in a salinity intercomparison (Farland, 1975). Considering only the sample bottles of nominal salinities 35.0 and 36.5‰, the maximum difference between the mean "errors" was .031‰ (or 0.012‰, if two ships are excluded). For a systematic error of 0.03‰, the dynamic height error would be 1.1 dyn cm at the surface. No temperature intercomparison was attempted, but it would require a systematic error greater than 0.1°C for temperature to degrade the calculations more than the salinity degrades them. The latter is not considered likely.

The variances of the individual data sets reflect primarily the temporal and spatial variation of the water. Typical numbers for the standard deviation from the means

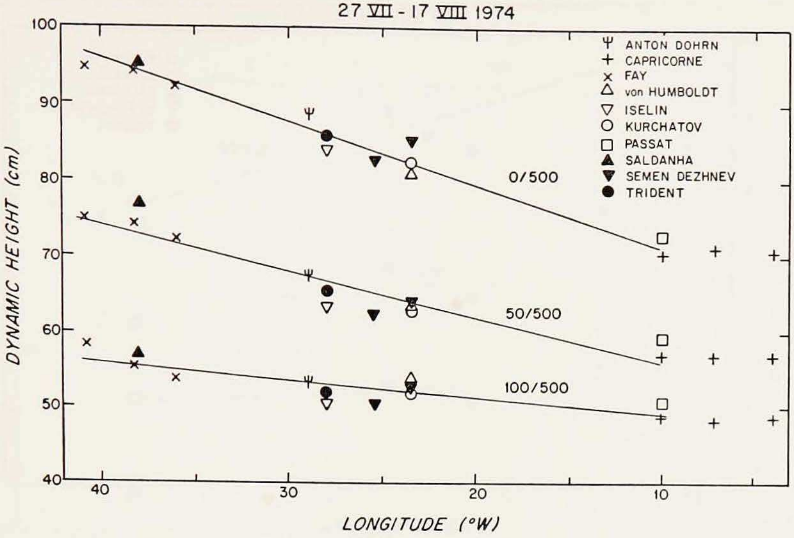

Figure 3. Dynamic height of the 0, 50, and 100 dbar surface relative to 500 during Phase II of GATE. Data points east of 10° W are excluded from the regression.

presented below are 2.3 dyn cm at 0/500, 1.3 at 50/500, and 0.7 at 100/500 (averages of the *Atlantis II* data) for single meridional sections, and about 1 dyn cm larger at each level for time series measurements (*Kurchatov, Passat* and *Saldanha* data). Thus, the uncertainty in a data point is as least as much a function of the variation in its own data set as it is due to the selection of a relatively shallow reference level or the differences between individual calibrations.

The results have been divided into three time frames: June 13-July 23, which includes data from pre-Phase I and Phase I, July 27-August 17, overlapping Phase II, and August 30-September 19, overlapping Phase III (Figs. 2-4). The 0/500 depicts the surface gradient against which the direct surface drag of the westward component of the wind competes and which it usually overcomes. The depth of the undercurrent shallows from west to east and 50/500 can be thought of as representative of the mean depth of the core of the undercurrent in the thermocline below the surface layer. One hundred meters is generally a depth below the maximum eastward current, below the strong vertical temperature gradient, and below the subsurface salinity maximum (when present) associated with the core of the undercurrent. It is, however, a depth of eastward flow.

To smooth the data and to attempt to derive from them an objective quantitative description which can then be used to compare different time periods, a linear fit was computed for the data west of 10°W. Each data point is equally weighted regardless of sampling method because the observed 16-day oscillation of the undercurrent during GATE suggests that a section and a three-week time series are

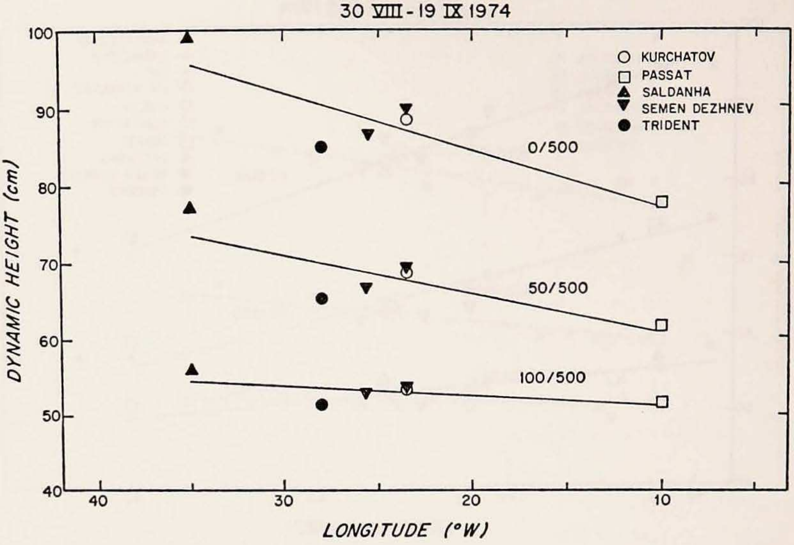

Figure 4. Dynamic height of the 0, 50, and 100 dbar surface relative to 500 dbar during Phase III of GATE.

roughly comparable with regard to aliasing. The use of linear regression to describe the data is not intended to assert that the zonal pressure gradient is necessarily constant. However, since the standard error of the estimated height for a given longitude during Phases I and II is less than 2.6 dyn cm, linear regression yields a result no less uncertain than that suggested by the variance in the data itself. The Phase III data, which shows the most variation from a linear fit, is unfortunately the least sampled. Excluding some of the data arbitrarily would yield a better linear fit; instead we have regressed the entire set and made the poor fit. The resulting zonal pressure gradients are given in Table 2.

Over the time span covered, the 100/500 surface goes from flat to a small inclination. The surface and 50/500 dbar gradients more than double between the first two sample periods and then possibly diminish. The surface gradient remains about 40% larger than the gradient at the 50/500 dbar level, despite the large changes in both.

Table 2. Zonal Pressure Gradient during GATE, West of 10°W. Units are 10^{-5} dynes/g. Numbers in parentheses are the standard errors of the linear regression coefficients.

	13 June-23 July	27 July-17 August	30 August-19 September
0/500	3.2(.4)	7.3(.6)	6.7(1.8)
50/500	2.2(.3)	5.3(.6)	4.7(1.6)
100/500	0.3(.2)	2.0(.4)	1.3(.7)

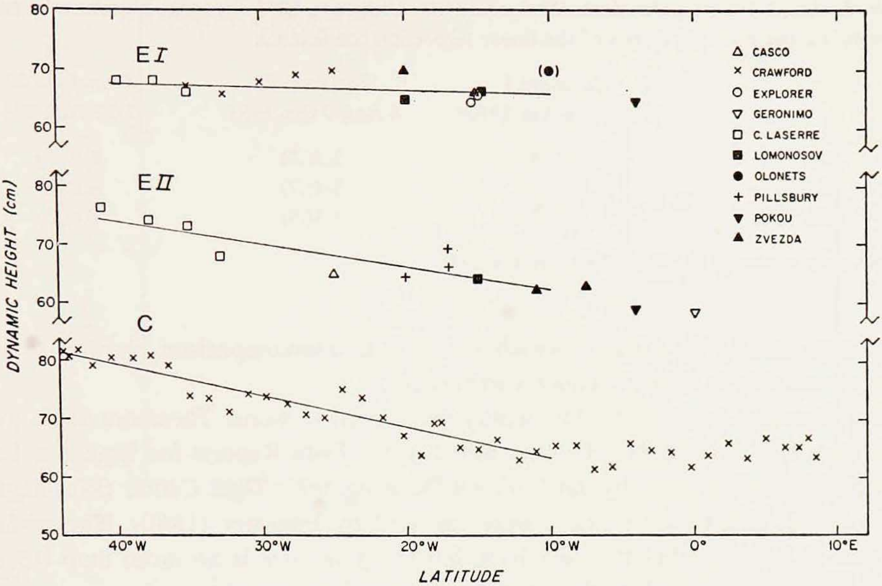

Figure 5. Dynamic height of 50/500 meter surface during Equalant I and II and *Crawford* cruise No. 22. Equalant data are meridional averages between 1°N to 1°S, generally including five stations. The *Crawford* 22 data are single stations on the equator. Regression analyses exclude observations east of 10°W. The *Olonets* observation is excluded because of abnormally high variance within the section. Occasional stations were excluded from Equalant data because of abnormal values.

3. Previous quasi-synoptic observations

Having observed an increase in the zonal pressure gradient during the summer of 1974, it is natural to ask if this increase is part of an annual cycle. While there is insufficient data to answer that question in an unambiguous manner, there are three previously reported synoptic observations. When these are combined with the GATE data, a working hypothesis can be proposed. Thus we examine two other cooperative international programs on the equator, Equalant I and II in 1963, and a single passage of closely spaced hydrographic stations along the equator by the R. V. *Crawford* during the International Geophysical Year (1958). These data, like the GATE data, are individually quasi-synoptic and cover the months March/April, August/September, and November, respectively. Data control is not as precise as with the GATE observations. With but one exception there are no time series; the data are from bottle stations as compared to the predominantly STD stations made during GATE; and the bottle spacing is not as heavily concentrated in the upper 200 meters as was the GATE hydrographic work. In the Equalant programs, there was no salinity intercomparison and shipboard salinity determina-

Table 3. Zonal Pressure Gradient, West of 10°W. Units are 10^{-5} dynes/g. Numbers in parentheses are the standard errors of the linear regression coefficients.

	Equalant I 25 Feb-16 Apr 1963*	Equalant II 4 Aug-9 Oct 1963	*Crawford* 22 12-29 Nov 1958
0/500	0.7(.6)	3.5(.7)	6.0(.3)
50/500	0.4(.2)	3.4(.7)	4.8(.3)
100/500	0.0(.2)	1.3(.5)	2.4(.3)

* An early section at 25°W, 8-10 Feb, is included.

tions were mainly by titration which the GATE intercomparison showed to vary widely from ship to ship and country to country.

The Equalant data are predominantly meridional sections. These are again averaged from 1°N to 1°S. The data are found in the Data Reports for Equalant I and for Equalant II, prepared by the National Oceanographic Data Center (Washington, D.C., 1964). The *Crawford* data were reported by Fuglister (1960). The surfaces are now in meters rather than decibars, but the difference is no more than 0.3 dyn cm at a given station and would not affect the slopes in any case.

The resulting 50/500 meter dynamic heights are shown in Fig. 5[4], along with the linear best fits of the data west of 10°W. Gradients of the 0, 50, and 100 m relative to 500 m surfaces are given in Table 3. Equalant II overlaps in season Phases II and III of the GATE experiment. Data from earlier in the year, Equalant I, are unique in having a relatively small slope. The *Crawford* zonal section is the only one of the observational periods which was densely sampled in the eastern Atlantic and it indicates that, to the east of 10°W (or perhaps further west), there is no further inclination to the surface. This result is not inconsistent with the few observations of the other data sets and it is the reason for considering 10°W as a mid-ocean limit.

Combining all the data so far discussed we can make a rough plot of the slope of the 50/500 dbar throughout a composite year (Fig. 6). It shows large variations which, if not a smooth continuous variation throughout the year, do suggest a seasonal trend. The Equalant I result of a barely resolved pressure gradient in March is followed by a still small gradient in June and July during Phase 0/I of GATE. Phases II and III of GATE suggest a maximum value in August with a slightly decreased gradient lasting at least through November (*Crawford* observations). Equalant II, in contrast, suggests either a smaller maximum gradient or a delayed build-up for that particular year. Until more data are forthcoming our best estimate is that the gradient is largest from August to December, with a typical

4. Equalant I and II dynamics heights have previously been presented by Williams (1966) and *Crawford* 22 by Neumann (1969). The calculations have been redone in order to achieve a uniformity of treatment with the GATE data and to exercise data quality control with the Equalant data. Williams, of course, comments about the disparity between the two Equalant results.

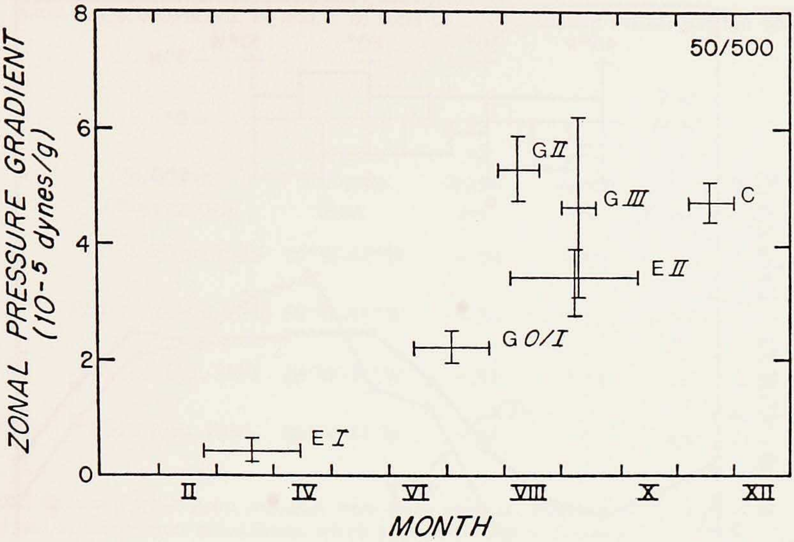

Figure 6. The Atlantic equatorial zonal pressure gradient west of 10°W as a function of the observational period and independent of year. The horizontal lines span the observational period of the data; the vertical lines describe the standard error of the regression coefficient.

value of about 5×10^{-5} dynes/g, and is smallest in March and April, with a value less than 1×10^{-5}. Only one transition period has been observed: in June/July during GATE.

4. Correlation of zonal pressure gradient to wind stress

It is generally assumed in theoretical work that the vertically integrated pressure gradient can be equated to the zonal component of the wind stress. Charney (1960) noted that this relationship held reasonably well from early estimates of the two quantities in the Pacific. A similar calculation for the data of Figure 6, approximating the integral by the gradient at 50 m, 5×10^{-5} dynes/g, multiplied by an effective depth of 100 m, suggests a wind stress of $-.5$ dynes/cm^2 for the latter half of the year and correspondingly lower values earlier.

Andrew Bunker of the Woods Hole Oceanographic Institution is presently analyzing the National Climatic Center marine observations for the Atlantic Ocean (designated as TDF-11) during the years 1941 through 1972. This data set allows for finer resolution than previous compilations (such as Hellerman, 1967) and Bunker has graciously permitted the use of his unpublished computations of monthly wind stress to help evaluate the correlation between pressure gradient and wind stress at the equator. The drag coefficients, data quality, etc. are detailed by Bunker (1976). The monthly mean wind stress, averaged from 10°W to 40°W, in a band

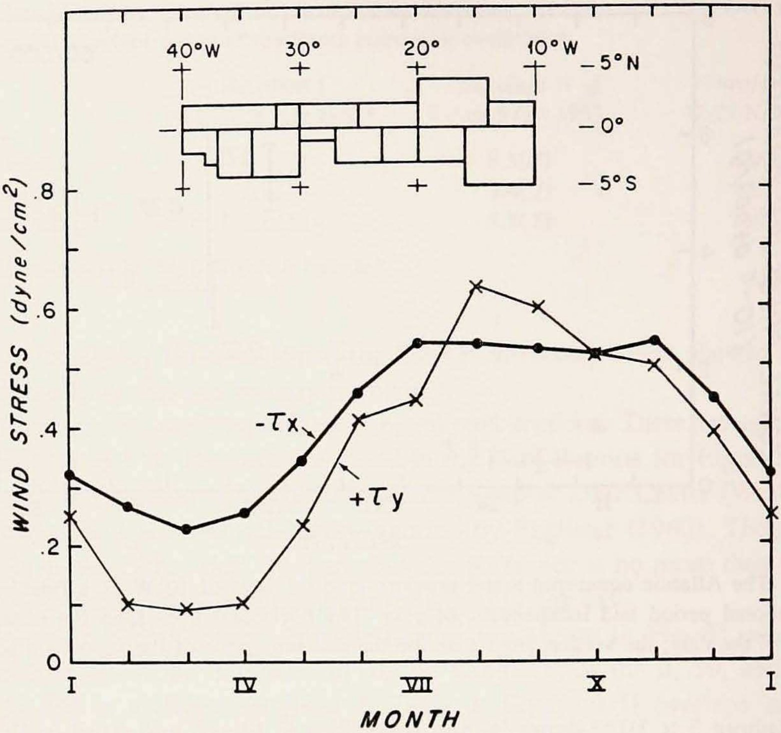

Figure 7. Monthly average wind stress on the equator averaged between 10°W and 40°W. The wind stress has been calculated by Bunker in the 14 subdivisions shown in the insert, from National Climatic Center TDF-11 tapes including marine observations from 1941 through 1972. The data points are arithmetic averages of the 14 subdivisions weighted by their zonal extent. τ_x and τ_y are the zonal and meridional components, positive in the easterly and northerly directions, respectively.

approximately 5° wide across the equator, is shown in Figure 7. The unevenness of the meridional coverage results from the subdivision of the data as finely as possible. For the purpose here, the closer to the equator the better, and only areas bounded on the equator are considered. In general, there are at least 100 observations for each month in each of the subdivisions. We note that the mean monthly zonal wind stress, from June through December, is within 10% of $-.5$ dynes/cm², the stress anticipated above. The earlier half of the year finds reduced values in both components of the wind stress; this reduction can be attributed to the annual meridional cycle of the intertropical convergence zone which is marked by a zonal band of minimum surface winds (Mintz and Dean, 1952). Seasonally averaged wind stresses for the Atlantic, being prepared by Bunker, show this meridional migration of minimum stress clearly.

The averaging between 10°W and 40°W, in Figure 7, was done to coincide with

Table 4. Wind stress between 2°N and 2°S, west of 10°W, during oceanographic observation periods.

	Period of Observations	Range of Observations	τ_x dynes/cm^2	τ_y dynes/cm^2	Pres. Grad. at 50 m 10^{-5} dynes/g	Comments
Equalant I	8 Feb-6 Apr, 1963	15°W-42°W	−.04	−.02	0.4	average of 12 sections*
GATE O/I	12 Jun-24 July, 1974	10°W-33°W	−.26	+.16	2.2	12 hourly obs., *Atlantis II*
Equalant II	4 Aug-9 Oct, 1963	10°W-40°W	−.37	+.54	3.4	average of 9 sections
Crawford 22	12-29 Nov, 1958	10°W-44°W	−.44	+.27	4.8	28 obs. on 0° N

* Excluded from the wind stress averages were three sections, observed at the end of the observation period and at the extreme zonal limits, which indicated a tenfold increase in τ_x.

the limits of the zonal pressure gradient. In fact, while the meridional stress does not vary much geographically through the area of interest for any given month, the zonal stress increases to both the west and the south. The extreme values cycle within a range of .0 to −.3 dynes/cm^2 in the NE sector of the band and a range of −.3 to −1.0 dynes/cm^2 in the SW corner. Nonetheless, the pattern of low values in late winter and high values in late summer repeats throughout the area, and the overall average is representative of the interior.

The wind stress cycle explains qualitatively the seasonal variation in the observed zonal pressure gradient and, quantitatively, the magnitude of the stronger pressure gradients recorded. Much more might not be expected from a comparison between climatic means and quasi-synoptic observations. The wind observations during the hydrographic work offer an opportunity to make a more direct comparison, thus the synoptically observed wind stresses during the oceanographic expeditions are given in Table 4. The drag coefficients used by Hellerman (1967), after Deacon and Webb, were used in these calculations as, unlike Bunker's, they do not require the not always available air/sea temperature difference. The differences between the coefficients are not large at moderate speeds and moderate temperature differences. The result not only repeats the correlation between the two components of the stress, it also indicates that the near zero pressure gradient observed in Equalant I was coincident with a nearly complete relaxation of the zonally averaged wind stress. Furthermore, the ratio of the zonal pressure gradient at 50 meters to τ_x is nearly constant (to an extent far better than the confidence in the data) and it is consistent with an effective depth of 100 m.

Interestingly, the derived relationship between stress and pressure gradient assumes a meridionally constant zonal wind stress in a wide enough equatorial band to include the region where the inertial forces are negligible (Charney, 1960). In fact, the zonal wind stress is not meridionally constant and if one averages the Hellerman (1967) data, which are given in 5° bands to either side of the equator, the seasonal cycle of τ_x is reduced in amplitude. Thus, while the derived relationship apparently holds, the assumption behind it, of small meridional variation in the zonal wind stress, is not substantiated observationally.

5. Correlation of undercurrent transport to zonal pressure gradient

Models also equate the transport to the zonal wind stress, linearly in linear models and more severely in nonlinear models (Gill, 1975). These steady state models do not distinguish between wind stress and pressure gradient and one might think of the pressure gradient as approximating a naturally weighted time and space average of the local wind stresses forcing the mean flow. But, evidence which would support or disprove the existence of a seasonal variation in the transport of the undercurrent is unavailable. After reviewing the literature, Philander (1973) concluded that there were insufficient data, unevenly reported, to address this question.

GATE data have not given any indication that the zonal transport was coherently altered during a period where the pressure gradient doubled although much could have occurred unobserved. Two meridians were monitored by current measurements during all three phases of GATE; 10°W (*Passat*) and 23°30′W (*Kurchatov*). Only the latter data set, which is derived from five surface moorings evenly spaced between 1.5°N and 1.5°S, can be used for transport calculations. The results have been reported by Bubnov *et al.* (1976) who found a 30 percent decrease in mass transport during Phase II relative to Phases I and III. The only other point of comparison that can be made is at 28°W. During Phase I a section by the *Atlantis II* yields a transport of 9.4×10^6 m^3/sec (Bruce and Katz, 1976), compared to the *Iselin's* average of 10.1×10^6 m^3/sec (Düing, personal communication) over continuously repeated sections throughout Phase II. All these estimates are based on integrating the transport within the eastward 20 cm/sec isotach.

Of special interest is the Equalant I observational period. The near zero pressure gradient occurred when the undercurrent was very much in evidence. The subsurface salinity maximum was well established across the Atlantic and seven observations of the undercurrent by subsurface drogues between 15°W and 30°W (Neumann and Williams, 1965; Stalcup and Parker, 1965), and six-day current meter records between 27°30′W and 32°30′W (Stalcup and Metcalf, 1966), observed averaged eastward currents of 50-80 cm/sec at depths representative of the undercurrent. Eastward surface currents were observed, as is usual when the wind stress on the surface is reduced (a phenomenon referred to as a surfacing of the undercurrent). Presumably, the undercurrent was deaccelerating at the time, but here again the observations are inadequate.

6. Comparison with the central Pacific

The question of seasonal variation in the zonal pressure gradient in the central Pacific was raised early by Austin (1958) and Knauss (1963) and, from the data then available, answered negatively. Two quasi-synoptic zonal sections have since been discussed extensively in the literature, that of the Dolphin expedition in May 1958 and the Alizé campaign in November 1964-February 1965. Knauss (1966) computed a gradient of 2.6×10^{-5} dynes/g from the former at the depth of the core of the undercurrent relative to 1000 dbar (which he shows fluctuating between 50-80 m) between 140°W and 104°W. For the latter, Lemasson and Piton (1968) show a dynamic height section from which one can compute a gradient of 4.8×10^{-5} dynes/g at 50/700 dbar and 3.3×10^{-5} dynes/g at 100/700 dbar between 160°E and 105°W. To the east of 140°W only, the pressure gradients are somewhat larger; the undercurrent core was found between 50 and 100 meters and the observations were made in the short time period of 20 November to 10 December, 1964. Thus, synoptic gradients in the central Pacific are in the range of the Atlantic observations cited here, with the exception of Equalant I.

Hickey's (1975) tide gauge data include multiyear overlapping records from five islands within 5° of the equator. The variations in sea level that the gauges record (mean seasonal range less than 10 cm, year-to-year fluctuations of less than 12 cm) can be compared to the more than 50 dynamic cm (Knauss, 1963; Lemasson and Piton, 1968) differential at the sea surface across the Pacific Ocean. Furthermore, the year-to-year variations were correlated between the five islands (0.5 to 0.9 zero lag correlation). The effect on the zonal pressure gradient suggested by these variations would appear to be relatively small.

Another measure of the seasonal variation of the zonal pressure gradient can be adduced from the charts of mean dynamic topography of the sea surface, relative to 1000 m, prepared by Wyrtki (1975) for the entire Pacific Ocean. They do not indicate any pronounced change in the slope along the equator from 180°W to 100°W when he compares March-April to November-December ("slightly stronger in the second half of the year").

7. Summary of conclusions

The GATE experiment clearly indicated an increase in the subsurface zonal pressure gradient, along the equator west of 10°W, from June/July to August in 1974, from 2.2 to 5.3×10^{-5} dynes/g, obtained from the slope of the 50/500 dbar surface. The latter surface represents the depth of the core of the undercurrent (i.e., maximum velocity) reasonably well over the time and space observed. A corresponding increase of the surface gradient, from 3.2 to 7.3×10^{-5} dynes/g is also noted. From August to September, an uncertain reduction of about 10% in both gradients is suggested.

Three historical data sets suggest that the larger gradient may persist through November, and that in March/April the gradient at least once (1963) almost disappeared. This latter singular observation, combined with the increase observed during GATE, leads us to suggest that there may be a seasonal trend to the pressure gradient.

A strong correlation between the zonal pressure gradient and the simultaneously observed zonal wind stress is noted for four observational periods, including the period in 1963 when both decreased to near zero. The latter occurred when the intertropical convergence zone intersected the equator, its maximum southerly position. From monthly wind stress data a 50% decrease in zonal wind stress is found to occur each boreal winter on the average. The wind observations reinforce the seasonal pressure gradient hypothesis but leave open the question of whether the nearly complete wind relaxation during the winter of 1963 was not just an extreme case of a usually more modest minimum.

The correlation between mass transport in the undercurrent and wind stress and/or pressure gradient is unresolved. The former is, of course, the most difficult to define and measure. We do know, however, that the undercurrent is at least present in the absence of both wind stress and pressure gradient and that we have no evidence for a direct correlation during the doubling of the pressure gradient in GATE.

All the oceanographic data from the Pacific Ocean suggest at most a limited seasonal fluctuation of the zonal pressure gradient there.

Acknowledgments. The decision to combine all the relevant GATE data was taken at a workshop held in Geneva in August, 1975. Each of the collaborating investigators assumed the responsibility of analyzing his own data set. John Bruce and Elizabeth Schroeder of Woods Hole assisted in the analysis of the *Crawford* and Equalant data. Our work was supported by the National Science Foundation under grant number ATM73-00344. Douglas Luther helpfully commented on this work while it was in progress. George Philander is warmly acknowledged for his constant interest and participation in the GATE equatorial field program from its inception. The article is Woods Hole Oceanographic Institution Contribution No. 3831.

REFERENCES

Austin, T. S. 1958. Variations of depth of oceanographic properties along the equator in the Pacific. Trans. Amer. Geophys. Un., *39*, 1055–1063.

Bruce, J. G. and E. J. Katz. 1976. Observations in the Equatorial Atlantic during GATE, June and July, 1974, from *Atlantis II*. Woods Hole Oceanographic Institution Tech. Rept. No. 76-54, Woods Hole, MA, 90 pp.

Bubnov, V. A., K. V. Moroshkin, V. D. Egorikhin, and Z. N. Matveeva. 1976. Variability of currents in the equatorial Atlantic. Oceanology, *16*, 408–415 (in Russian).

Bunker, A. F. 1976. Computations of surface energy flux and annual air-sea interaction cycles of the North Atlantic Ocean. Monthly Weather Rev., *104*, 1122–1140.

Charney, J. G. 1960. Non-linear theory of a wind-driven homogeneous layer near the equator. Deep-Sea Res., *6*, 303–310.

Düing, W., P. Hisard, E. Katz, J. Meincke, L. Miller, K. V. Moroshkin, G. Philander, A. A. Ribnikov, K. Voigt, and R. Weisberg. 1975. Meanders and long waves in the equatorial Atlantic. Nature, *257,* 280–284.

Farland, R. J. 1975. The GATE report on salinity intercomparison. World Meteo. Org. (Geneva), 31 pp.

Fuglister, F. C. 1960. Atlantic Ocean Atlas, Woods Hole Oceanogr. Inst. Atlas Series, Vol. 1, Woods Hole, MA, 209 pp.

Gill, A. E. 1975. Models of equatorial currents, *in* Numerical Models of Ocean Circulation. Nat. Acad. Sci., Wash., D.C., 181–203.

Hellerman, S. 1967. An updated estimate of the wind stress on the world ocean. Monthly Weather Rev., *95,* 607–626 (as corrected).

Hickey, B. 1975. The relationship between fluctuations in sea level, wind stress and sea surface temperature in the equatorial Pacific. J. Phys. Oceanog., *5,* 460–475.

Knauss, J. A. 1963. Equatorial current systems, *in* The Sea, Vol. 2, M. N. Hill, ed., New York, Interscience, 235–252.

—— 1966. Further measurements and observations on the Cromwell Current. J. Mar. Res., *24,* 205–240.

Lemasson, L. and B. Piton. 1968. Anomalie dynamique de la surface de la mer le long de l'équateur dans l'Océan Pacifique. Cah. ORSTOM, Sér. Océanog., *6,* 39–45.

Mintz, Y. and G. Dean. 1952. The observed mean field of motion of the atmosphere. Geophys. Res. Papers. No. 17. Cambridge, MA, 65 pp.

Neumann, G. 1969. The equatorial undercurrent in the Atlantic Ocean, *in* Proc. Symp. Oceanog. and Fisheries Resources of the Tropical Atlantic, UNESCO, Paris, 33–44.

Neumann, G. and R. E. Williams. 1965. Observation of the equatorial undercurrent in the Atlantic Ocean at 15°W during Equalant I. J. Geophys. Res., *70,* 297–304.

Philander, S. G. H. 1973. Equatorial undercurrent: measurements and theories. Rev. of Geophys. and Space Phys., *11,* 513–570.

Stalcup, M. C. and W. G. Metcalf. 1966. Direct measurements of the Atlantic equatorial undercurrent. J. Mar. Res., *24,* 44–55.

Stalcup, M. C. and C. E. Parker. 1965. Drogue measurements of shallow currents on the equator in the western Atlantic Ocean. Deep-Sea Res., *12,* 535–536.

Williams, R. G. 1966. An investigation of the intermediate salinity maximum in the equatorial Atlantic during Equalant I. New York Univ. Tech. Rept., GSL-TR-66-4, New York, N.Y., 93 pp.

Wyrtki, K. 1975. Fluctuations of the dynamic topography in the Pacific Ocean. J. Phys. Oceanog., *5,* 450–459.

Received: *20 September, 1976;* revised: *30 November, 1976.*