In situ wind measurements in the equatorial Atlantic during 1979

Surface winds
Atlantic Ocean
Equator
Global Weather Experiment

Vents de surface
Océan Atlantique
Équateur
Expérience Mondiale de Météorologie

S. L. Garzoli [a], E. J. Katz [a], H.-J. Panitz [b], P. Speth [b]
[a] Lamont-Doherty Geological Observatory, Palisades, New York 10964, USA.
[b] Institut für Geophysik und Meteorologie, Universität Köln, FRG.

Received 25/11/81, in revised form 1/2/82, accepted 30/3/82.

ABSTRACT

In situ wind measurements near the equator are described in the central Atlantic during the Global Weather Experiment in 1979. There are two data sets: a year-long record from St. Peter and St. Paul Rocks (29°W) and several records from surface buoys along 22°W during the first half of the year. In general, the data are found to agree with historical means for their respective areas and reproduce the expected trends in both space and time. Wind speed autospectra reproduce the slopes of other marine observations at very different sites and indicate enhanced variance at high frequencies (semi-diurnal to inertia-gravity waves). Spatial coherence at lower frequency (10-20 days) between the two locations is not consistently observed and at 4-6 days appears during one time period but not another. The GOES-East cloud derived winds are compared with the data from the rocks, and it is found to record the correct monthly wind for six months during the strong trade-wind period (with a 9° turning angle), but to completely miss the annual relaxation to lighter trade winds.

Oceanol. Acta, 1982, **5**, 3, 281-288.

RÉSUMÉ

Mesures directes du vent
dans l'Atlantique équatorial en 1979

Les mesures directes du vent dans l'Atlantique équatorial, qui ont été obtenues au cours de l'Expérience Mondiale de Météorologie (1979) sont décrites. Deux ensembles de données sont disponibles : 1 an d'enregistrement aux Rochers St. Pierre et St. Paul (29° W) et plusieurs enregistrements provenant de bouées de surface, le long du méridien 22° W, au cours de la première moitié de l'année. Dans l'ensemble, les données sont cohérentes avec les données « historiques » moyennes de la région et reproduisent bien les variations attendues dans l'espace et dans le temps. Des spectres rendent compte des tendances constatées dans d'autres observations océaniques en des sites très différents; ils indiquent une augmentation de la variance aux fréquences élevées (ondes semi-diurnes à ondes d'inertie-gravité). La cohérence spatiale aux plus basses fréquences (10-20 jours) n'est pas constante; pour la gamme 4 à 6 jours elle n'apparaît que dans certaines périodes de temps et pas dans d'autres. Les vents estimés à partir des observations des nuages par le satellite GOES-East sont comparés aux données provenant des Rochers St. Pierre et St. Paul; on constate une bonne cohérence dans les périodes de vents alizés forts (à un angle de rotation de 9° près) mais les périodes d'alizés faibles ne sont pas du tout décrites.

Oceanol. Acta, 1982, **5**, 3, 281-288.

LDGO contribution n° 3332.

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INTRODUCTION

Knowledge of the surface wind field is of central importance for studies of upper ocean dynamics. In low latitudes, where geostrophy is not applicable and consequently quasi-geostrophic models are not adequate to establish the wind field, *in situ* measurements are essential. Until recently only ship observations were available to describe the wind field over most of the tropical ocean. A climatology of the surface wind field in the equatorial Atlantic has been extracted from these data (Hastenrath, Lamb, 1977). The northeast and southeast trade winds are seen to prevail over the western part of the Atlantic Ocean. The tradewinds converge on the Intertropical Convergence Zone (ITCZ) which migrates with the seasons: in March, west of 20° W, it is practically along the equator; by August it is north of 10°N (Hellerman, 1980). Among its many meteorological expressions, the ITCZ is a region of low surface wind. Its migration signals a change in both wind speed and direction and therefore results in a seasonally variable forcing on the upper layer of the ocean.

This note describes *in situ* observations of the wind obtained during the Global Weather Experiment in 1979 near the southern position of the ITCZ in the central Atlantic. Two sets of data are analyzed: 1) a 1-year record obtained from a wind recorder located at St. Peter and St. Paul Rocks (SPP) (1°N, 29°W); and 2) concurrent meteorological measurements along 22° W, from 1°S to 3°N, between January 30, 1979 and June 6, 1979, from surface buoys deployed by the research vessel « Meteor ».

In the tropical Atlantic, observations and theoretical models (e. g., Katz *et al.*, 1977; Philander, Pacanowski, 1980) indicate that the adjustment time of the ocean to wind forcing is rapid enough to impose an annual cycle on the ocean. The 1-year record at SPP gives a representation of the complete annual cycle of the wind in the central Atlantic. Contrary to the Pacific Ocean, where a few equatorial islands can be used as bases for meteorological stations, the rocks are the only land in the equatorial Atlantic far from continents. It is therefore an ideal and unique site for observing open sea winds in the equatorial Atlantic without introducing errors due to topographic effects or platform motion. To our knowledge, these observations are the longest *in situ* measurements in the region.

The data density provided by ship observations in the equatorial Atlantic is not uniformly adequate to quantify interannual differences in the seasonal wind cycle or to resolve higher frequency oscillations. Satellite observations (e. g., low-cloud movements and sea surface scatterometers) may provide uniform data of the large scale wind field on a regular basis later in this decade. At the moment we are at an intermediate stage between ship observations and operationally validated satellite derived sea surface winds. There are two methods of validating satellite winds: by comparison with ship observations (Krishnamurti, Krishnamurti, 1980) and with buoy or island observations (e. g., Halpern, 1978). As long records are so difficult to obtain and due to the fact that satellites offer several possibilities for estimating winds, the wind record at SPP is compared to the cloud derived winds provided by NOAA/NESS. The analysis is made to determine the extent to which low-cloud motion vectors differ from surface wind measurements and to what extent they could be useful to monitor the trade wind cycle.

THE INSTRUMENTS

St. Peter and St. Paul Rocks

The wind recorder is a modified vector averaging current meter made by AMF with a cup anemometer replacing the savonious rotor, a shielded thermistor mounted in an extended arm (and vaned to face into the wind) to measure air temperature and a capacitive-type pressure transducer to measure atmospheric pressure (Payne, 1974). Each sensor is sampled every 112.5 seconds and recorded every hour. The instrument stood vertically in a tower with its sensors 3 m above the ground (see Fig. 1). Wire mesh was wrapped around the rotor and vane platform to keep away the local population of birds and crabs. It was calibrated with the wire mesh (about 20% speed reduction).

The wind recorder was placed on St. Peter and St. Paul Rocks. The rocks are a series of outcroppings of the mid-Atlantic ridge 1 000 km from the nearest land mass. The four largest rocks form a horseshoe cove, open to the NE, extending 200 m north/south and 120 m east/west (US Defense Mapping Agency Hydrographic Center, Chart 24521). The largest rock is in the southwest and on its highest point (about 23 m) is located the remains of a small light-house. The tower is implanted on a second high spot (about 20 m above sea level) 25 m due south of the lighthouse. As shown in Figure 1, it has an unobstructed view of the Southeast Trades (indicated by the vane direction). Its location is 0°55.13′N, 29°20.60′W. The instrument was operational from February 2, 1979 to January 23, 1980, during the time of the Global Weather Experiment.

Figure 1

Wind recorder at St. Peter and St. Paul Rocks [SPP, (0°55′N, 29°24′W)].

The surface moorings

Five surface moorings were deployed at 1°S, at the equator and at 1°N, 2°N, 3°N at 22°W. Figure 2 shows the positions and gives the times of surface wind recording. The meteorological equipment consisted of an Aanderaa data-logger, an anemometer, a vane and compass, and a thermistor to measure the sea surface temperature. The wind registrations were based on the measurement of electric resistance, and the wind speed was averaged over time intervals of 10 or 20 min. Figure 3 shows one of the buoys and the meteorological equipment.

Hourly averages of speed, direction and of the zonal and meridional components were calculated from those surface registrations.

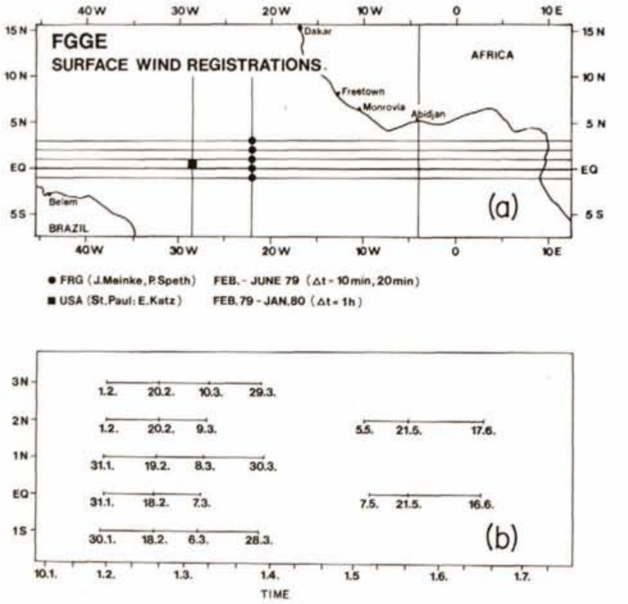


Figure 2

a) position of wind recording: (●) surface moorings, (■) SPP; b) times of surface wind recording at 22°W.

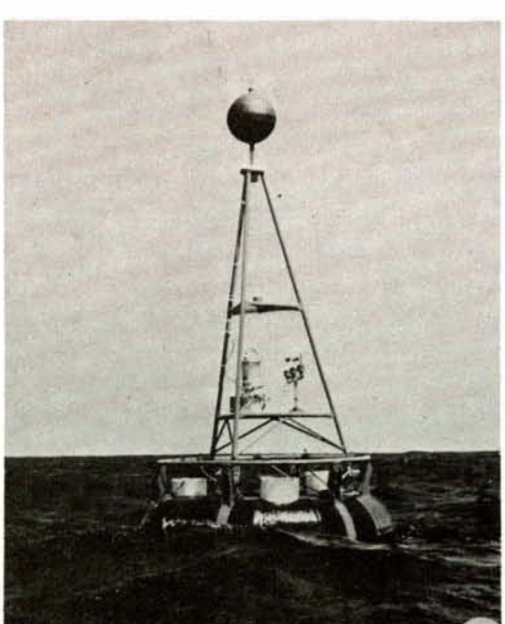


Figure 3

Buoy and meteorological equipment deployed at 22°W.

The five moorings had to be recovered at the end of March 1979. The recordings at the equator and at 2°N had stopped on March 7 and 9, respectively. Two moorings were redeployed at the beginning of May 1979: one at the equator and the other at 2°N.

OBSERVATIONS

The wind speed

The daily averages of the wind speed at the different locations are shown in Figures 4 *a* and *b*. Figure 4 *a* (at SPP) shows the annual variation of the daily mean at 29°W, and Figure 4 *b* shows the meridional distribution at 22°W for two different periods.

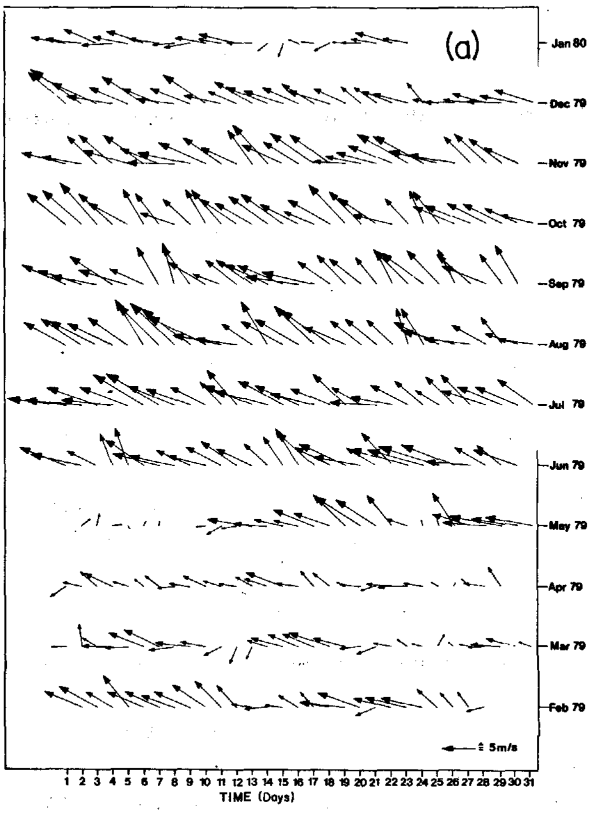
The monthly and 10-days steadiness values at SPP are given in Figure 5, upper curves. Figure 6 shows the daily variation of the steadiness at 22°W. The steadiness of the wind, defined as the ratio of the magnitude of the mean wind vector, $(\bar{u}^2+\bar{v}^2)^{1/2}$, to the mean magnitude, $\overline{(u^2+v^2)^{1/2}}$, expressed as a percentage, equals zero for winds which shift randomly and one hundred for winds that always blow in the same direction. Steadiness is generally above 90%, as expected from a tradewind region. In Figure 5 (1°N, 29°W), the solid line corresponds to the monthly steadiness and the dashed line to the 10-days steadiness. From March to May the monthly steadiness value is 13% less than the rest of the year. Stronger zonal winds are continuously steady, making the area a particularly good one to model with a slowly varying large scale wind forcing.

At 22°W (Fig. 6) the winds are very stable from May to June but less stable during February and March. At 29°W (Fig. 5), the near zero magnitude of the meridional wind component during March indicates the confluence of the ITCZ during which the wind briefly changes from SE to NE trade. This result is in agreement with previous results; for example, the analysis made by Hellerman (1980) from historical data. He concludes that the ITCZ, which migrates with the seasons, is practically along the equator during March in this region.

The ITCZ brings low values of wind steadiness. Toward the east, at 22°W, the lowest value of the daily steadiness appears to occur earlier than at 29°W.

We must remark that we are comparing values of 10-days steadiness with 1-day steadiness which means two different definitions (as can be seen in Figure 5 for monthly and 10-days steadiness). But in this case, at both 0° and 1°N, 22°W the lowest value of the steadiness is so pronounced ($\sim 30\%$) compared with the adjacent values that we can assume that the intercomparison is valid.

At 22°W (Fig. 6) it occurs during February. At 29°W (Fig. 5) the situation is more complicated. The low value of the 10-days steadiness during March is associated with the earlier minimum to the east. The lowest value of the steadiness during May is due to episodic shifts of zonal wind direction and not to a



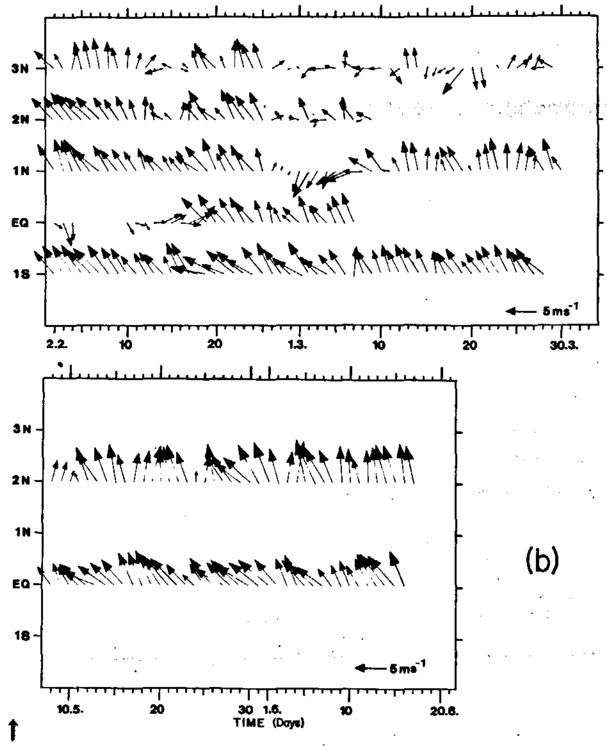


Figure 4
Daily mean variation of the wind speed at SPP (Fig. 4a) and at 22°W (Fig. 4b).

change in the meridional wind component (see Fig. 5, lower curves).

The annual averaged meridional direction (at 29°W) was towards the north ($v=2.2$ m.sec.$^{-1}$), and the zonal wind component was westward ($u=-4.6$ m.sec.$^{-1}$). The total speed V is compared with the historical data (Hastenrath, Lamb, 1977) in Figure 7. The two representations of the monthly averaged wind speeds, one climatic and the other a single realization, are highly correlated ($r=0.95$). Though the mean trend is the same, the difference in amplitudes of the annual means ($V_{SPP}=5.5$ m.sec.$^{-1}$; $V_{H\&L}=3.9$ m.sec.$^{-1}$) is about 30%. Only 5% of this difference can be attributed to the difference in observation height. However we still cannot conclude that 1979 was a particularly "windy" year because the Hastenrath and Lamb atlas also includes spatial averaging.

The wind stress (inferred)

The main interest of oceanographers, when considering the response of the ocean to the wind forcing, is the behavior of the time-dependent wind stress. This was estimated using the relation:

$$\vec{\tau}=\rho\, C_Z\,|\vec{U}_Z|\,\vec{U}_Z, \tag{1}$$

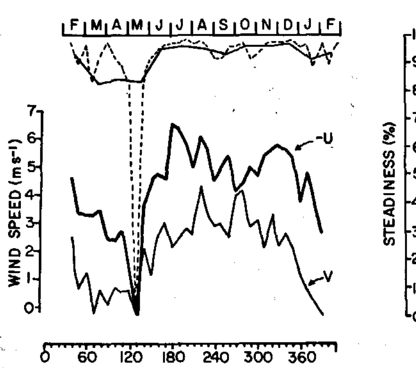


Figure 5
Annual variation of the 10-days averaged components of the wind. Upper curves: solid line, monthly steadiness; dashed line, 10-days steadiness.

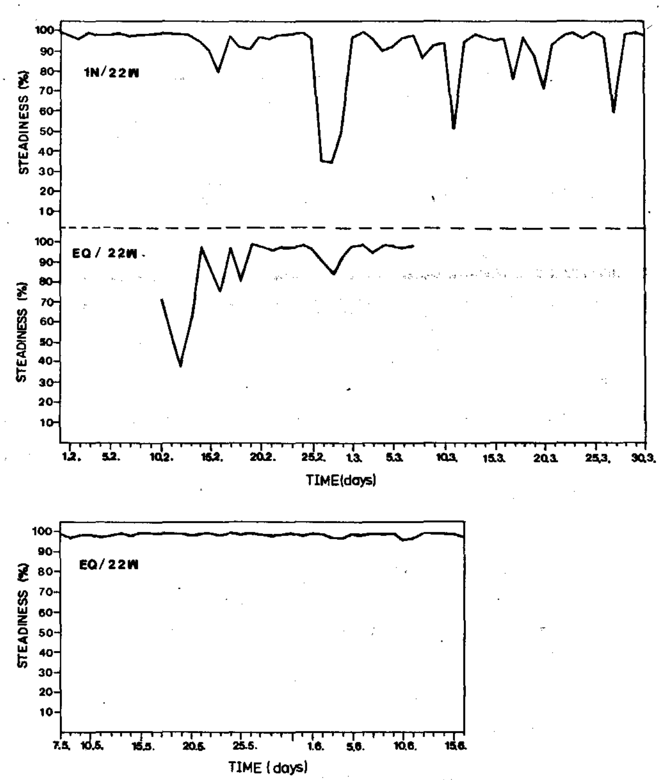


Figure 6
Daily variation of the wind steadiness along 22°W. Top: 1°N January 31, 1979 to March 30, 1979, 0°, February 10, 1979 to March 7, 1979; bottom: 0°, May 7, 1979 to June 16, 1979.

Figure 7
Total speed at SPP (solid line) compared with historical data from Hastenrath and Lamb atlas (dashed line).

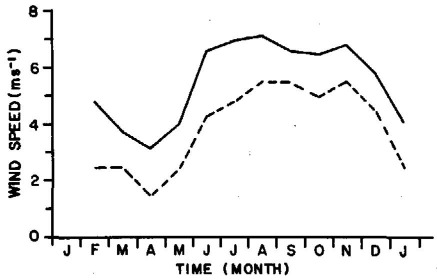
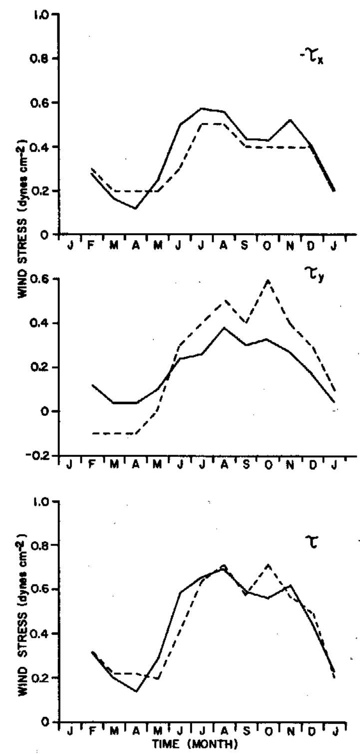


Figure 8
Annual variations of the wind stress components (solid line). a) zonal; b) meridional and the total wind stress at SPP. Superimposed (dashed line) the wind stress components and the total wind stress as derived from Bunker's data for the region 0 to 2°N, 30 to 32°W.



where ρ=density of the air and C_Z is the wind stress coefficient. The wind stress coefficient was estimated as a function of the observed velocity U_Z at $Z=21.3$ m. It was derived from simultaneously solving the equations:

$$\frac{U_Z}{U_*} = \frac{1}{k}\ln(Z/Z_0), \tag{2a}$$

$$Z_0 = U_*^2\, a/g, \tag{2b}$$

where U_Z is the wind velocity at a height Z above mean sea level, U_* is the friction velocity of the wind, k is the von Karman constant and Z_0 is the roughness length of the sea surface. "a" is the so-called Charnock constant and, following Wu's analysis and review of relevant data (1980), we set it equal to 0.0185. If we use the relation $C_Z=(U_*/U_Z)^2$ and make a linear fit for wind speeds between 5-20 m.sec.$^{-1}$ at $Z=21.3$ m height, we have:

$$C_Z=(0.743+0.0479\, U_Z).10^{-3}, \tag{3}$$

and we can then compute the wind stress directly from the wind record.

Results are compared with the wind stress components derived by Bunker (derived from Bunker and Goldsmith, 1979; period of record: 1948-1972) using a variable coefficient which depends on stability for the region 0 to 2°N, 30 to 32°W (Fig. 8). A comparison of the total wind stress is also shown in Figure 8. There is good correlation between Bunker's data and those at SPP for both $\vec{\tau}$ and τ_x despite the differences in data sets and meteorology. The historical average of the meridional component τ_y shows a change in the sign that is not reproduced in our record. They may be due to the more northerly extent of the historical data including stronger NE trades further to the north of the ITCZ during these months.

The annual mean for wind stress and wind stress components are:

	τ	τ_x	τ_y
Bunker	0.44	−0.33	0.22
SPP	0.44	−0.37	0.19

We can conclude that, with respect to annual means and monthly annual variations, the record obtained at SPP during 1979 is in very good agreement with the historical data. One could hardly have anticipated that any one year would agree so well with the climatic mean. The onset of the winds in 1979, however, occurs one month earlier than the historical mean.

The meridional variation of the wind and wind stress at 22°W is shown in Figure 9. The wind stress was computed using (2) at the height of the instruments ($Z=21.3$ m). Values for the first observation period are dashed, while those in the second observation period are fully drawn (notice that the time intervals for the buoys at the equator and at 2°N are shorter than the others). It is seen that the mean wind and the wind stress are decreasing from south to north in the first observation period. In the second observation period the wind is stronger with a more meridional orientation at 2°N. Mean values, for a similar time period at SPP are shown in Figure 9. Comparison of these values with those at 22°W show that the zonal component is increasing from east to west; the opposite holds true for the meridional component. These statements are comparable to historical data (Fig. 3 in Düing *et al.*, 1980).

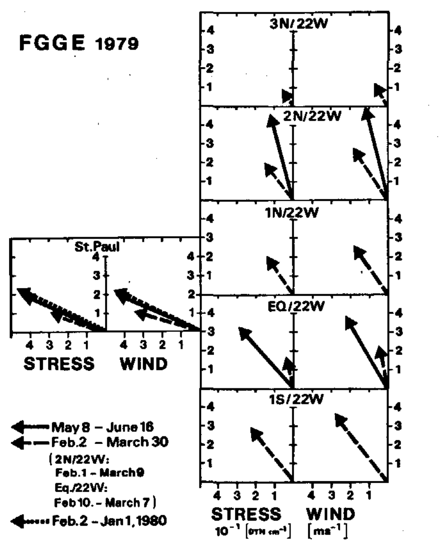


Figure 9
Mean values of wind and wind stress for a similar time period at 29 and 22°W.

SPECTRAL ANALYSIS

The power density spectra for the wind components at SPP are displayed in Figure 10*a* and *b*. Both show a decrease in energy density with frequency with a slope of −1.4 for frequencies between 0.1 and 10 c.p.d. This drop-off of energy with increasing frequency in the equatorial Atlantic has the same slope as found by Halpern (1980) 1 000 km to the north (8°41′N, 23°10′W), Shaw *et al.* (1978) in the western North Atlantic, Burt *et al.* (1974) in the eastern North Atlantic, and Halpern (1978) in the central equatorial Pacific.

The spectra of the u (zonal) and v (meridional) components of the wind (Fig. 10) show an increase in the variance at the diurnal period. Those oscillations are only significant at the 95% confidence level in the total wind spectrum. The r.m.s. amplitude of the u, v and V $(=(u^2+v^2)^{1/2})$ diurnal period variations as computed from the spectra are 0.28, 0.22 and 0.34 m.sec.$^{-1}$, respectively. Agreement is noted with other equatorial wind observations. Halpern (1979) reported an r.m.s. amplitude of the u and v diurnal period variations of each about 0.30 m.sec.$^{-1}$ at 7°N, 150°W. They were not coherent over 100 km meridionally and in his spectra the fluctuations at the semidiurnal period were less than the diurnal. Peddler (1978), from Gate data at 8°N, 24°W, found a significant diurnal and semidiurnal period surface wind oscillation, each with amplitudes of about 0.25 m.sec.$^{-1}$. The increased variance at the diurnal period in equatorial wind records may be due to diurnal convective effects, beside purely tidal forcing, a phenomenon suggested by Gray and Jacobson (1977).

The spectrum of the meridional component of the wind shows an increase in the variance at both 3.75 and 2.14 days. Energy at similar inertia-gravity frequencies in both the surface wind and the ocean been reported in the Pacific by Groves and Miyata (1968), Wunsch and Gill (1976), Luther (1980), and in the Atlantic by Halpern (1979), and Horigan and Weisberg (1981). In a recent paper, Garzoli and Katz (1981) have shown that the ocean spectra in the western Atlantic from inverted-echo sounder records is similar to the spectra of the meridional component of the wind at those frequencies (i. e., energetic at 3.75 and 2.14 days). They conclude that the oceanic oscillations are forced by the wind.

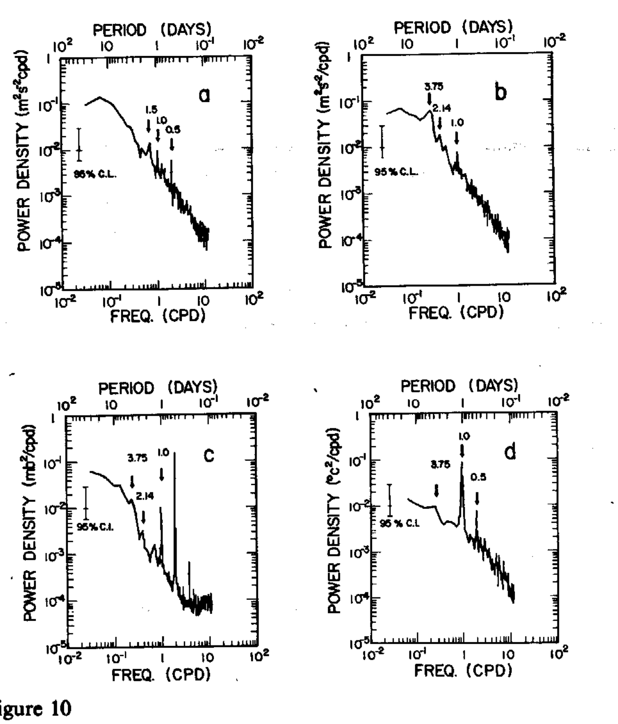


Figure 10

Power density spectra for: the zonal (a) and meridional (b) wind components; air pressure (c) and air temperature (d). Data from SPP.

The spectra of the air pressure (Fig. 10*c*) shows significant increase in the variance at the diurnal and semidiurnal periods. The r.m.s. amplitude of the diurnal variations is 0.41 mbar and for the semidiurnal periods, 0.74 mbar. Those values are in good agreement with the means observed at the equator, where they reach their maximum values of 0.6 and 1 mbar for the diurnal and semidiurnal periods, respectively (Haurwitz, 1965; Kertz, 1956). According to Lindzen's (1967) theory of tides in the atmosphere, the smallness of the diurnal surface pressure oscillation results from most of the thermal drive being used to activate modes trapped in the stratosphere due to ozone excitation.

The air temperature spectrum (Fig. 10*d*) shows an increase in the variance at the diurnal period larger than at the semidiurnal period. The r.m.s. amplitudes are 0.32 and 0.10°C, respectively. We attribute the strong diurnal effect to local heating during the day, rather than to atmospheric tides.

The coherence spectra for the wind components at 22°W and 29°W, for two coincident time periods, are shown in Figure 11. The records are short and data intervals occur during transitional times at 29°W, but the absence of any previous simultaneous *in situ* wind records from the central Atlantic moves us to comment on what we have.

In the February/March period the zonal components appear to be coherent at periods of 10 to 20 days. These are energetic periods (see Fig. 10*a*). In May/June, however, it is the meridional components which are coherent. The result is therefore mixed and leaves unanswered the question of whether or not winds measured along the equator, 800 km apart, are coherent at low frequency.

At higher frequencies, there is an indication of both zonal and meridional coherence at 4 to 6 days in the latter time period. This is attributable to inertia-gravity waves propagating westward in the atmosphere. Albignat and Reed (1980) have shown from GATE wind data that during the period 23 August-19 September 1974, all stations west of 10°E (the observations extend to 20°W and lie between 0 and 10° N) exhibited pronounced spectral peaks at periods of 3-4 days. According to Burpee (1972), the physical mechanism of the origin of the waves intensifies during the period from June to October. The significant coherence in Figure 12 might be attributable to this westward propagation, which would explain why it is not seen earlier in the year. The phase between them at 4 days is 60° (not shown), which suggest a wavelength of 5 000 km. This is not statistically different from the values of 3 800 km given by Burpee (1974) for easterly waves at 4.5 day periods.

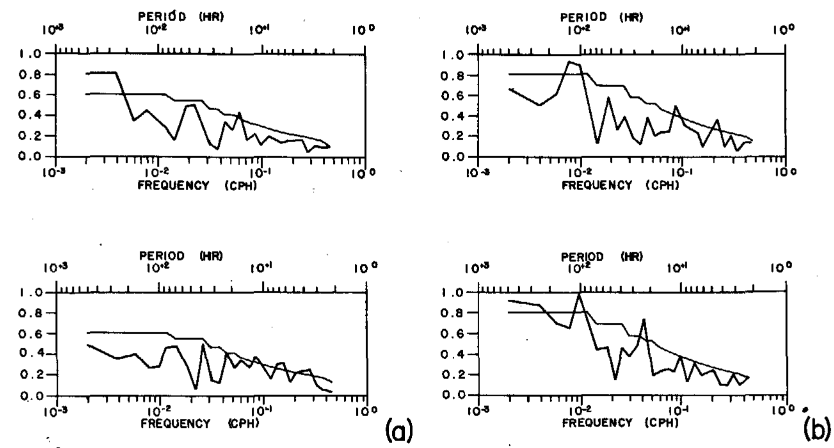


Figure 11
Coherence spectra for wind components at 22°W and 29°W for two coincident periods, a) February 2, 1979 to March 30, 1979; b) May 7, 1979 to June 16, 1979. Upper (lower) panels depict the zonal (meridional) coherences.

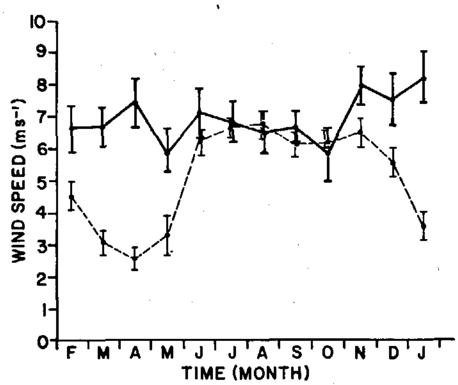


Figure 12
Annual variation of the monthly mean vector averaged speed $(u^2+v^2)^{1/2}$ from the CDW (solid lines) compared with the same parameter at SPP. Confidence limits correspond to the standard errors.

SATELLITE DATA

During the period of wind observations at SPP, the NOAA's Geostationary Operational Environmental Satellite East (GOES-East) was operational in the area. The eastern longitude limit is 25°W, for latitudes between 45°N and 45°S. Cloud motion vectors are derived operationally by NESS via manual and automatic techniques. In the manual technique, the motion of the clouds were observed directly from satellite photographs.

Although we do not expect the low-level cloud motion vectors and the wind recorder measurements to be identical, a comparison is made between the two sets of data to determine to what extent the cloud derived winds (CDW) represent the mean features needed as input to oceanographic models at the equator.

The CDW, received on tape from NOAA/NESS, are processed to daily and monthly mean resultant vectors in the area 30° to 32°W, 2.5°N to 0°. As the wind recorder at SPP is located in the eastern edge (1°N, 29°W) of GOES-East and, as the quality and number of observations decrease toward the edges of the satellite, this is the nearest area with a reasonable number of observations to be compared. During the operational year of the wind recorder (February 1979 to January 1980) there are 686 NESS-CDW observations. No comparison is possible with the records at 22° W. A preliminary analysis showed that the speeds of manual CDW are considerably greater ($>30\%$) than the picture-pair derived. A similar result was found by Sadler and Kilonsky (1981), who concluded from comparisons in the Pacific that the automatic analysis agreed better with ship observations. As the manual CDW represents only 12% of the total data, the analysis was done considering only the automatic CDW.

The monthly means of the speed derived from the CDW during the year do not show the mean trades as observed at SPP. CDW speeds are almost constant during the whole year (Fig. 12). The weakening of the trades associated with the migration of the ITCZ towards the equator, and the strengthening associated with the retreat of the ITCZ, are not reproduced by the CDW as directly derived from NESS tapes.

What is remarkable is that, for 5 months during the time period of high steadiness, the values of the monthly means of $(u^2+v^2)^{1/2}$ at SPP and CDW are statistically the same, suggesting that winds are the same at the surface as at 800 mbar. We compared the 10-day averaged time series of the CDW components u and v with those at SPP for the period in which the steadiness is higher than 95% (June to December). Components are estimated using a turning angle of 9° (clockwise from cloud to surface), and this value corresponds to the mean angle difference between SPP and CDW directions from June to December. We must notice that 9° is in good agreement with the range of turning angles for the region (8-15°) given by Krishnamurti and Krishnamurti (1980) in their analysis during the 100 days of GARP (July through September, 1974) in the tropical Atlantic. 10-day averaged time series are coherent ($r^2=0.50$, 0.49 and 0.30 for correlations between $(u^2+v^2)^{1/2}$, u and v respectively) between June and October, but incoherent for November and December. The CDW speeds reported for those two months are 25% higher than the rest of the year.

DISCUSSION

The annual cycle of the wind near the equator in the central Atlantic (29°W) is characterized by a weakening of the winds from March to April associated with the presence of the ITCZ over that part of the ocean. The migration of the ITCZ clearly appears from the simultaneous analysis of the records at 29°W and 22°W. At 22°W the lowest value of the daily steadiness appears during February; at 29°W the 10-days steadiness has a low value during March. The *in situ* annual cycle described here agrees with the climatic mean. The zonal component of the wind stress increases from east to west, and this result is also in agreement with the historical data.

The spectral analysis of the wind components shows an increase in the variance at the diurnal and semi-diurnal tidal frequencies. At the inertia-gravity frequencies significant variances are found in the meridional component spectrum, but this phenomenon is not present in the zonal wind spectrum. These results are typical of equatorial surface wind observations in general.

The cloud derived winds by NOAA/NESS cannot be directly used as input to solving oceanographic problems related to the wind forcing. While it is of interest to know the interannual variation of the magnitude of the trade winds, something which may be obtainable from the NOAA/NESS CDW product, it is essential to be able to identify when this tradewind is established and dies out each year. The present comparison with an *in situ* record confirms that the CDW does not yield this vital information. Periods of low winds are related to the presence of the ITCZ near the equator. The resulting convective activity creates an upper level cloud layer which obscures lower level clouds that at other times of the year gives a good estimate of sea surface winds.

In addition, we are dealing with data at the edge of GOES-East which means diminished viewing angles and optical deformation. More elaborate and costly treatment of the GOES-East data such as that which is being done at the University of Wisconsin will give better results (Gautier, pers. comm.). However, surface observations will be necessary for some time to come to calibrate the turning angles and to determine the steadiness in the region. *In situ* measurements, as described in this note, is the best method of obtaining quality observations of the wind in the oceans.

Acknowledgements

We appreciate the cooperation of the Brazilian Government for permission to place the wind recorder on St. Peter and St. Paul Rocks, and the assistance of Pr. Afranio de Mesquita of the University of São Paulo with the initial deployment from the research vessel « Professor Besnard ». Subsequent landings were made from the research vessels « Conrad » and « Oceanus ». Calibration of the recorder and processing of the data were supervised by Dr. Richard Payne of the WHOI Buoy Group. Richard Nowak, also of WHOI, designed and implemented the deployment.

The moored wind recorders were deployed from the R/V " Meteor".

Discussions with Dr. Catherine Gautier of the University of Wisconsin Space Science and Engineering Center about GOES and METEOSAT clouds derived winds and with Zulema Garraffo, GFDL, Princeton University, about atmospheric tides, are gratefully acknowledged.

The research was supported by National Science Foundation grants OCE 77-25142, OCE 79-22532 and ATM 81-09197 and by the Deutsche Forschungsgemeinschaft.

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