THE VARIABILITY OF THE SURFACE WIND FIELD
IN THE EQUATORIAL PACIFIC OCEAN: CRITERIA FOR SATELLITE MEASUREMENTS

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ABSTRACT

The natural variability of the equatorial Pacific surface wind field is described from long-period (1.0-2.5 years) surface wind measurements made at three sites along the equator (95°W, 109°30'W, 152°30'W). These data, which were obtained from surface buoys moored in the deep ocean far from islands or land, provide adequate criteria to adequately sample the tropical Pacific winds from satellites.

1.   INTRODUCTION

Variations in the surface wind field in the equatorial Pacific yield rich responses in the upper ocean circulation and thermal fields; the generation of Kelvin waves (Knox and Halpern, 1982) and of the spectacular 1982-83 equatorial Pacific warm event (Halpern et al., 1983) are two examples. While knowledge of the large-scale spatial and temporal structures of the tropical wind field is essential to our understanding of global ocean-atmosphere climate variability, our techniques to describe the fluctuations of the surface wind field are poor and require much improvement. Because the wind and mass fields are not strongly coupled in low latitudes, quasi-geostrophic models are inadequate, and wind observations are more important than atmospheric pressure measurements. Wind observations from ships, cloud-tracking via satellite measurements, and satellite microwave measurements are three techniques that provide wind coverage over large areas in low latitudes. Sampling of winds by ships is too sporadic in time and space, especially for scales smaller than about one month and 1000 km, e.g., within 10° of the Pacific equator the data base for the 1947-72 wind climatology produced by Wyrtki and Meyers (1976) consisted of approximately 3 observations per day per 10° square. Winds determined from cloud drift observations are considered an interim solution until such time (perhaps as early as 1989) as continuous measurements (e.g., microwave radiometer, radar altimeter, multi-directional scatterometer) are made from satellites. In the design of a satellite wind measuring system, the orbit configuration, mission duration, geographical coverage, footprint dimensions, accuracy and resolution of measurements, time interval between repeated orbits, and verification and ground truth studies must all be considered in the context of the natural variability of the surface wind field. This paper describes the variability of surface winds measured continuously at a few locations in the tropical Pacific remote from islands and land. Possible errors in the satellite measured wind field will be discussed.

2.   DATA AND INSTRUMENTATION

Moored wind measurements were made at 3.5-3.8 m height with a vector-averaging wind recorder (VAWR) mounted on a 2.44 m diameter toroidal surface float supporting
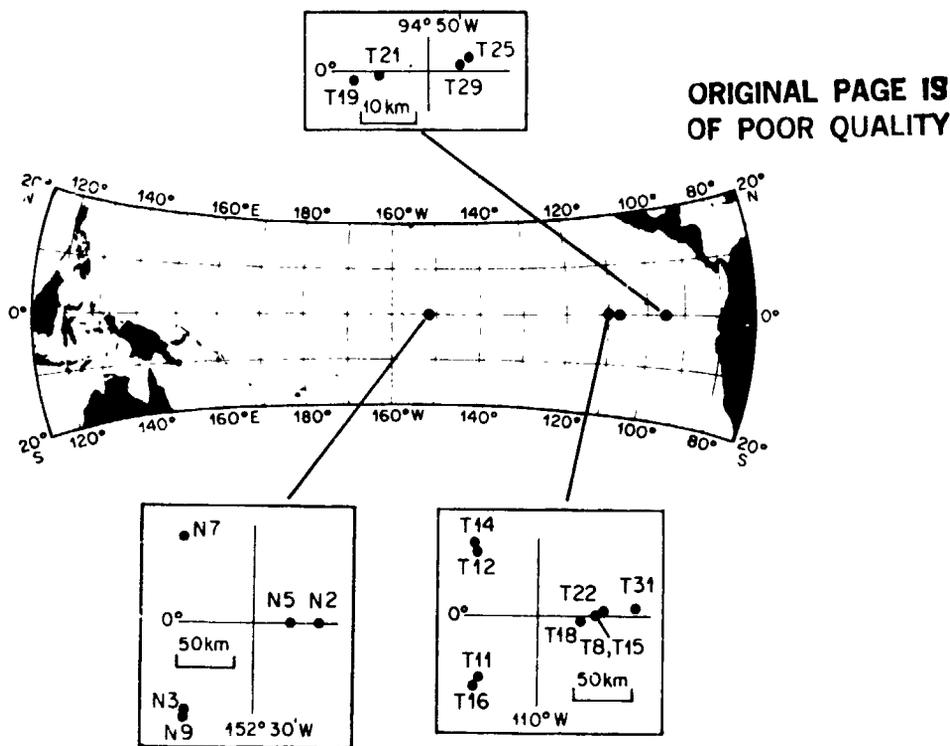
Figure 1. Locations of equatorial moored wind measurements described in this paper. Water depths at the mooring sites varied from about 3400 to 5100 m. The closest equatorial islands are the Galápagos Islands (~ 0°, 91°W) to the east and Jarvis Island (~ 0°, 160°W) to the west. Deployment intervals were about four to six months. At 0°, 95°W the mooring intervals were: T19, 4 July - 25 October 1981; T21, 7 November 1981 - 2 April 1982; T25, 4 April - 4 November 1982; and T29, 5 November 1982 - 18 April 1983. The 0°, 108°W site (mooring T27; 00°01.0'S, 108°00.2'W) began in April 1982. The mooring durations at 0°, 109°30'W were: T8, 10 August 1980 - 5 February 1981; T15, 7 February - 9 July 1981; T18, 11 July - 28 October 1981; T22, 31 October 1981 - 15 April 1982; T31, 27 October 1982 - 23 April 1983; T12, 11 August 1980 - 31 January 1981; T14, 2 February - 7 July 1981; T11, 13 August 1980 - 3 February 1981; and T16, 4 February - 11 July 1981. Near 0°, 152°30'W the mooring intervals were: N2, 24 April - 9 October 1979; N3, 30 April - 9 October 1979; N5, 13 October 1979 - 9 February 1980; N7, 16 February - 2 June 1980; and N9, 16 February - 2 June 1980.

a 3 m high aluminum tower with a platform on top. Figure 1 summarizes the locations and record-lengths of the equatorial Pacific wind measurements used in this paper. The VAWR was mounted through a hole in the platform, with the heights of the 9 cm x 17 cm balanced wind vane and Climet model 011-2B 3-cup anemometer were about 0.5 m above the platform. The VAWR operated continuously and recorded integrated values of east-west (u; positive eastward) and north-south (v; positive northward) speeds at 15 min intervals. The anemometer was calibrated at eight speeds over the range 1.5-24.5 m s^{-1} in the wind tunnel of the Atmospheric Sciences Department, University of Washington, before and after the observation periods. The after- and before-calibration curves differed by less than 0.1 m s^{-1} at speeds below 10 m s^{-1} and about 0.2 m s^{-1} at 15 m s^{-1}.

Mooring motion is known to contaminate wind measurements made from surface-following buoys which move horzontally and vertically to follow the contour of the sea surface. Visual observations indicate that the rotational motion about the buoy's vertical axis (i.e., yawing) is negligible. However, the pitch and roll motion of the buoy can increase the apparent scalar averaged wind speed, cause
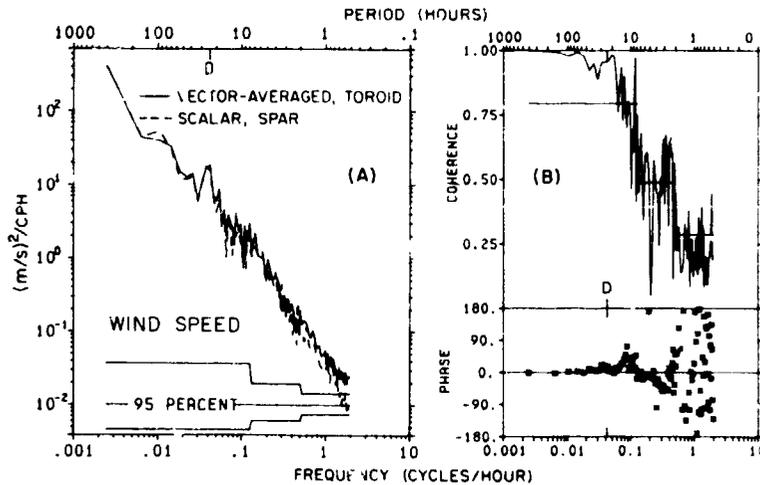
Figure 2. (A) Spectral estimates of wind speed fluctuations. (B) Coherence and phase difference between spar buoy scalar speeds and toroidal buoy vector-averaged speeds. The "95 percent" represents the 95% confidence levels determined from the chi-square distribution and applicable to each curve. The three short horizontal lines drawn on the plot of the magnitude of the coherence represent the 95% confidence limits. In (A) and (B), D indicates the diurnal frequency.

overspeeding of the 3-cup anemometer, and cause the anemometer to measure over a range of heights. It was found (Figure 2) that for frequencies below 0.5 cycle per hour (cph), VAWR wind speed measurements recorded from a vertically stable spar buoy and our surface-following buoy were nearly identical and highly correlated, indicating a negligible influence of mooring motion. In the intercomparison test the surface-following buoy and spar buoy were separated by 10 km; had they been closer together, the frequency corresponding to 0.5 cph probably would have been higher. There was no evidence of a distinct spectral flattening (i.e., a less rapid decrease of spectral estimates with increasing frequency) at frequencies >1 cph, which a priori was expected if mooring motion and sensor noise contributed spurious motions to the measurements. Since the 15-min vector-averaged wind speeds were rarely greater than 10 m s^{-1}, a speed equivalent to surface wave amplitudes $\geq$ 1 m, the wind sensors were practically never in the shadow of a wave crest unless the swell was unusually large.

Record gaps occurred because instrumentation did not always operate properly, buoys broke loose from their mooring line, and buoy recovery operations usually preceded deployments. The 1-2 day record gap resulting from mooring recovery and deployment operations at four to six month intervals was filled by linear interpolation. The 13-month record at 0°, 152°30'W was formed by combining the 24 April 1979 - 9 February 1980 data at 0°, 152°W with the 16 February - 2 June 1980 measurements at 0°37'N, 153°04'W. In the 29-month record at 0°, 109°30'W a six month (April - October 1982) segment was measured at 0°, 108°W. On different occasions moored wind observations were also recorded at sites approximately 75 km north and south of the equator near 153°W and 110°W. As will be shown (Figure 5), for frequencies below about 2-3 cycle per day (cpd) the surface wind vectors were coherent at the 95% confidence level with zero phase difference, indicating that time variations of the low-frequency wind vectors occurred simultaneously over distances up to 150 km. The 50% noise level occurred at about 1 cpd.

3. OBSERVATIONS

At 95°W, 109°30'W and 152°30'W the vector-mean wind directions were representative of southerly, southeasterly and easterly trade winds, respectively,

Table 1. Statistics of 2-hour vector-averaged east-west (u; positive eastward) and north-south (v; positive northward) wind components. Wind direction is defined as the direction (clockwise from true north) in which the wind is blowing. See text for definition of steadiness.

	0°, 152°30'W 24 Apr 79-2 Jun 80	0°, 109°30'W 10 Aug 80-20 Dec 82	0°, 95°W 4 Jul 81-19 Apr 83
Mean u (m s^{-1})	-5.2	-3.6	-1.5
Mean v (m s^{-1})	0.6	3.1	3.9
Standard deviation u (m s^{-1})	2.0	1.7	2.0
Standard deviation v (m s^{-1})	1.6	1.7	2.1
Vector-mean speed (m s^{-1})	5.6	5.1	4.8
Vector-mean direction (°T)	277	311	338
Mean steadiness (percent)	94	95	90

i.e., the surface wind vector from 95 to 152°W rotated counterclockwise (Table 1). (Wind direction is defined as the direction in which the wind is blowing.) This pattern is similar to the 1947-72 climatological-mean wind distribution computed by Wyrtki and Meyers (1976). The vector-mean wind speed, which was not large (~ 5 m s^{-1}), and the mean zonal wind speed increased toward the west; in contrast, the mean meridional wind component increased dramatically eastward (Table 1). The magnitude of the variability of the 2-hour wind data, as measured by the standard deviation, was generally equivalent to about 50% of the mean speed; on occasions the standard deviation was greater than the mean speed (Table 1).

The steadiness of the monthly wind is defined as the ratio of the magnitude of the monthly mean wind vector, $(\bar{u}^2 + \bar{v}^2)^{\frac{1}{2}}$, to the monthly mean magnitude, $\overline{(u^2 + v^2)^{\frac{1}{2}}}$, expressed in percent. The u and v values are the 2-hour averaged data and an overbar represents a calendar-month time average. The steadiness is primarily a measure of directional variability; steadiness equals zero for winds which shift randomly and have a zero resultant speed, and equals one for winds which always blow in the same direction. A feature of the trade wind is its relatively high steadiness (Table 1). At each site the lowest monthly steadiness value (39% at 95°W; 76% at 109°30'W; 86% at 152°30'W) was associated with the smallest vector-averaged monthly wind speed (1.1 m s^{-1} at 95°W; 2.6 m s^{-1} at 109°30'W; 3.4 m s^{-1} at 152°30'W). The anomalously low monthly wind speed at 95°W happened in February 1983 when the normally occurring easterlies collapsed and became westerlies because of the spectacular 1982-83 El Niño Southern Oscillation (ENSO) episode. The arrival of ENSO winds at 95°W in February 1983 and their persistence through the end of our observations in April (Figure 3C) caused the relatively low value of the record-length mean steadiness, e.g., prior to the January 1983 arrival of the ENSO winds at 95°W the July 1981-December 1982 steadiness was 96%, which is similar to the values obtained at 109°30'W and 152°W.

Although the wind data were relatively steady in direction, the u and v series often contained quite intense mesoscale activity with time scales from a few days to a few weeks (Figures 3A and 3B). While the 15-min vector-averaged recorded data were very seldom in excess of 10 m s^{-1}, the trade wind was interrupted by relatively calm conditions (March 1981 at 109°30'W (Figure 3B)) and by an ENSO related prolonged reversal in direction (March-April 1983 at 95°W (Figure 3C)). The 1982-83 ENSO westerly wind originated in the western Pacific and propagated across the Pacific at about 1 m s^{-1}; however, it is not usual for the trade wind in the eastern Pacific to reverse direction even during an El Niño. Monthly mean surface wind speeds ranged from about 3 to 7 m s^{-1} with seasonal wind speed changes typically 2-3 m s^{-1} and interannual variations of 1-2 m s^{-1} in the central Pacific (Figure 3C).

Spectral estimates of the u and v time series with zero mean value and zero least-square linear trend were computed from Cooley-Tukey Fourier transforms using the perfect Daniell frequency window of variable width (Figure 4). For each spectrum the sum over positive frequencies was equal to the total variance. For
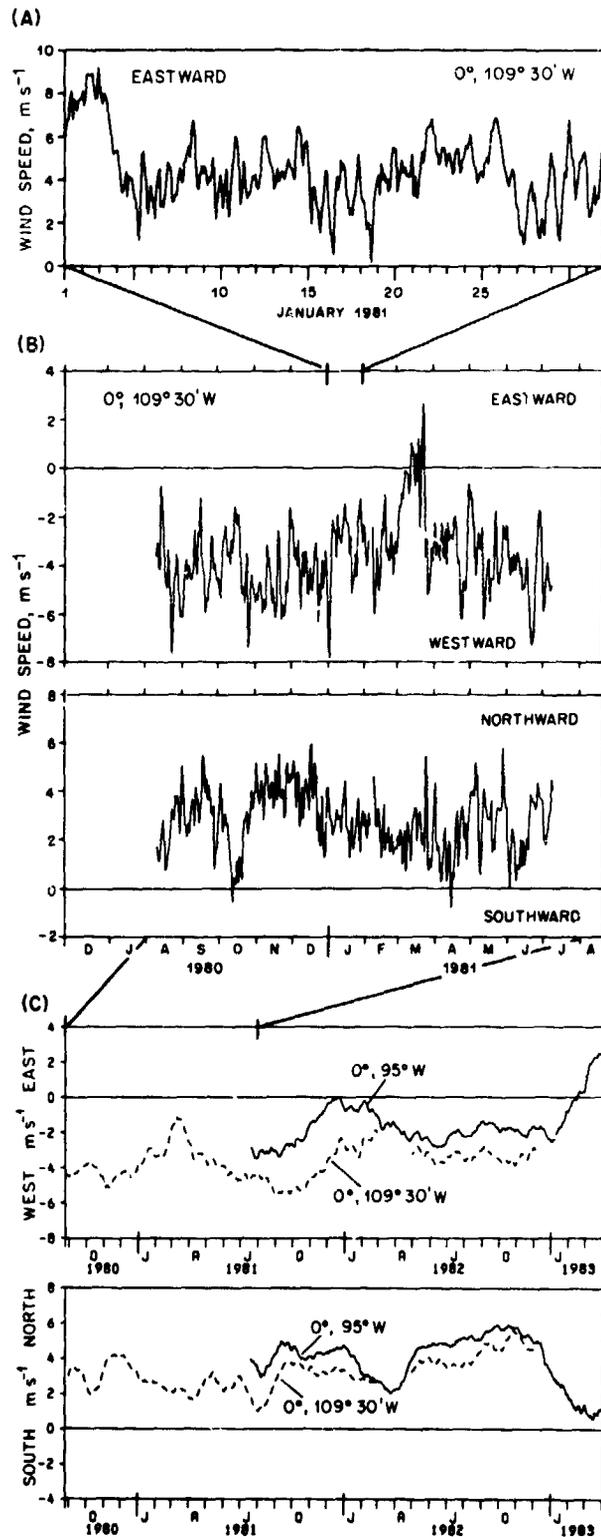
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Figure 3. Time series of moored wind measurements. (A) Two-hour vector-averaged
values of zonal wind at 0°, 109°30'W during January 1981. (B) Daily vector-averged
values of zonal and meridional wind at 0°, 109°30'W from August 1980 to July 1981.
(C) Low-pass (31-day running mean) filtered zonal and meridional wind data at 0°,
109°30'W (dashed line) and 0°, 95°W (solid line).

the u component (Figure 4A) there was a 1:1 correspondence between the shapes of
the 95°W, 109°30'W and 152°30'W spectra for frequencies greater than 1 cpd; the
152°W u spectra did not show evidence of a diurnal peak rising above the
background. At 95°W and 109°30'W the u spectra were similar for all frequencies.
For the v component (Figure 4B) the spectral shapes had a 1:1 correspondence above
0.25 cpd. A distinct 0.03-0.3 cpd spectral flattening occurred in the v spectrum
at 152°30'W. At 95°W the spectral levels of u and v were fairly similar throughout
the frequency range, except at the tidal frequencies; at 110°W the u component
spectral levels were greater than the v series from about 0.02 to 0.2 cpd, and at
152°W the u and v spectral shapes and levels were dramatically different for
frequencies below 0.2 cpd, with u values being significantly greater. At
frequencies above ~ 0.25 cpd the spectral levels decreased uniformly with
increasing frequency (except at tidal frequencies), with a slope of about -1.25 for
each of the u components, -1.3 for the v component at 95°W and 109°30'W, and -1.5
for the v component at 152°30'W. At the diurnal period the amplitude of v was
greater than u at each of the equatorial sites; the diurnal period rms amplitude
was much smaller at 152°W (Table 2). The maximum spectral peak within the 3-7 day
band occurred in v at 152°W; at 95 and 110°W it is unclear whether wind energy in
this frequency range was greater than the background level.

Figure 5 shows the magnitudes of the coherences and phase differences between
simultaneous wind measurements made in two small-scale regions near the equator,
one at 109°30'W (Figure 5A) and the other at 152°W (Figure 5B), and along the
equator between 109°30'W and 95°W (Figure 5C). For frequencies below about 2-3 cpd
the wind vectors near 0°, 109°30'W were generally coherent at the 95% confidence
level, with zero phase difference over the small-scale buoy array (Figure 5A); a
similar result was found at 152°W (Figure 5B). Thus, for distances up to at least
150 km the time variations of the low-frequency wind vectors occurred
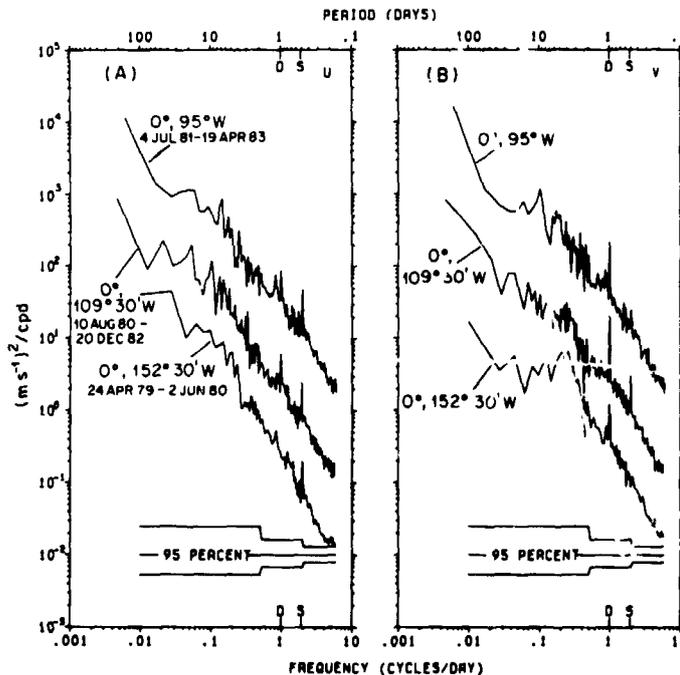
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Figure 4. Spectral estimates of (A) zonal and (B) meridional wind components at the
three equatorial sites. The 109°30'W and 95°W spectral levels are plotted,
respectively, one and two decades higher than measured. The "95 percent"
represents the 95% confidence levels determined from the chi-square distribution
and applicable to each curve. D and S indicate the diurnal and semidiurnal
frequencies.

Table 2. Root-mean-square amplitudes of wind measurements for different frequency
intervals. Units = m s^{-1}. For analysis of diurnal and semidiurnal motions, a
405.3 day record-length was used at each site; at 95°W and 109°30'W simultaneous
observations during 4 July 1981 to 14 August 1982 were used. At lower frequencies
the rms amplitudes were computed over the maximum record-length: 24 April
1979 - 2 June 1980 at 152°30'W; 10 August 1980 - 20 December 1982 at 109°30'W;
4 July 1981 - 19 April 1983 at 95°W.

	0°, 152°30'W	0°, 109°30'W	0°, 95°W
Semidiurnal u	0.10	0.07	0.11
Semidiurnal v	0.06	0.10	0.10
Diurnal u	0.11	0.14	0.19
Diurnal v	0.25	0.26	0.30
0.143-0.333 cpd v	0.93	0.61	0.75
0.033-0.1 cpd u	0.56	0.57	0.64
0.033-0.1 cpd v	1.23	0.79	0.75
0.1-6.0 cpd u	1.27	1.13	1.21
0.1-6.0 cpd v	1.39	1.10	1.36

simultaneously. If the velocity fluctuations are linearly related, then 100 times
the square of the coherence (i.e., 100 Coh^2) represents the percentage of the total
variance which can be explained by a linear relationship existing between two wind
records, and the quantity (1-Coh^2) represents the noise and/or nonlinear
relationship. The 50% noise level occurred at about 0.3-0.5 cpd at 109°30'W and
0.5-1.0 cpd at 152°W. For longer separation distances such as the 1600 km between
the measurements at 95°W and 109°30'W, the wind vectors were coherent with 95%
statistical significance within selected time scales: in u and v, the seasonal
time scale of 100 days or more; in v, the 3-5 day and diurnal periods; and in u and
v, the semidiurnal period (Figure 5C). Only at the seasonal time scale was the
magnitude of the large-scale coherence greater than the 50% noise level.

4. RESULTS

Along the equator at 95°W, 109°30'W and 152°30'W the u and v spectral levels
decreased with increasing frequency, falling off roughly as $f^{-1.25}$ to $f^{-1.5}$
(f = frequency). Similar spectral slopes have been observed in the Intertropical
Convergence Zone (ITCZ) region in the Pacific near 6-8°N, 150°W (Halpern, 1979) and
in the eastern Atlantic (Halpern, 1980). Comparing the 0°, 152°30'W wind
observations with similar measurements made at 7°N, 150°W during 7 November 1977 to
22 March 1978 (see Halpern (1979) for wind characteristics at 7°N, 150°W), which at
that time was located under the ITCZ, shows (Figure 6) that the 7°N u and v
spectral estimates were consistently higher than the 0° estimates, especially above
1 cpd for the u and v values and below 0.2 cpd for the v component. The greater
variability at higher frequencies at 7°N was probably due to cloud cluster motions
associated with convergence along the ITCZ. The dramatic difference of the v
spectral estimates below 0.15 cpd suggests a latitudinal attenuation of large-scale
meridional motions (perhaps associated with easterly waves primarily confined to
the equatorial trough).

Of the wind measurements recorded at 95°W, 109°30'W and 152°30'W, only the v
spectrum at 152°30'W contained indications of a 3-7 day spectral peak (Figure 4)
with rms amplitude of nearly 1 m s^{-1} (Table 2). It is tempting to speculate that
the amplitude of the statistically (at the 95% confidence level) significant
meridional (but not zonal) wind energy at 4-5 days at Canton Island (2°46'S,
171°43'W) (Wunsch and Gill, 1976) diminishes eastward. The origin of the 4-day
meridional wind oscillation is unclear. The u and v spectral shapes of the Canton
Island and 152°30'W wind data were very similar.

At frequencies below 2-3 cpd and over north-south or east-west distances of
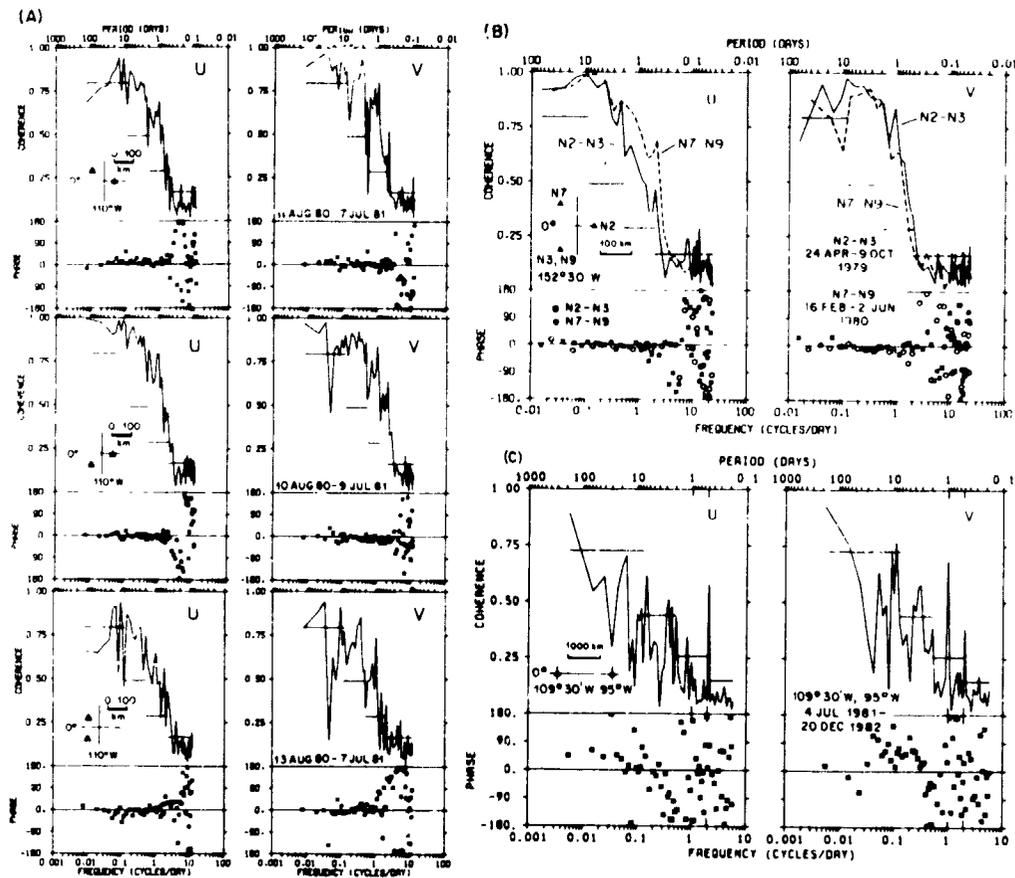150 km the wind fluctuations near 0°, 109°30'W and 0°, 152°30'W were coherent (at

Figure 5. Magnitude and phase difference of the coherence between simultaneous wind measurements from small-scale buoy arrays near (A) 0°, 110°W and (B) 0°, 152°30'W, and (C) between 95°W and 109°30'W. Locations of wind data and durations of measurements are shown within the u and v (respectively) coherence magnitude diagrams. The four short horizontal lines in the magnitude portion of the diagram represent the 95% confidence limit of the coherence estimate. In (C) a positive phase difference corresponds to the wind variation occurring earlier at 95°W than at 109°30'W.

the 95% confidence level), with little phase difference. This maximum-coherent-frequency (mcf) was nearly 10 times greater than the mcf observed over similar distances along 150°W near the ITCZ (Halpern, 1979), presumably because of the considerable amount of small-scale atmospheric motions, such as C-scale convection, occurring near the ITCZ. The ~ 0.5 cpd frequency of the 50% noise level associated with the ~ 150 km scale arrays near 1 9°30'W and 152°30'W was about 3 times greater than Halpern (1979) found at 150°W under the ITCZ. While there was little evidence of a 0.2-0.35 cpd spectral peak at 95°W and 109°30'W (Figure 4), apparently these fluctuations were coherent (at the 95% confidence level), with about a 45° phase difference, which corresponds to a 0.5 day time delay for a 4-day easterly wave; the coherence magnitudes were less than the 50% noise level (Figure 5).

If the observed time/space scales (100 day/1600 km and 0.5 day/150 km) are joined by a line, then by interpolation the horizontal distance associated with coherent wind fluctuation for one month time scale would be ~ 1250 km. That this value is greater than the one determined by extrapolation from the small-scale array near 7°N, 150°W (Halpern, 1979) is consistent with the higher frequency-wavenumber variability occurring near the ITCZ.

The v component spectrum (Figure 4B) at each of the 3 equatorial sites contained statistically significant (at the 95% confidence level) diurnal-period
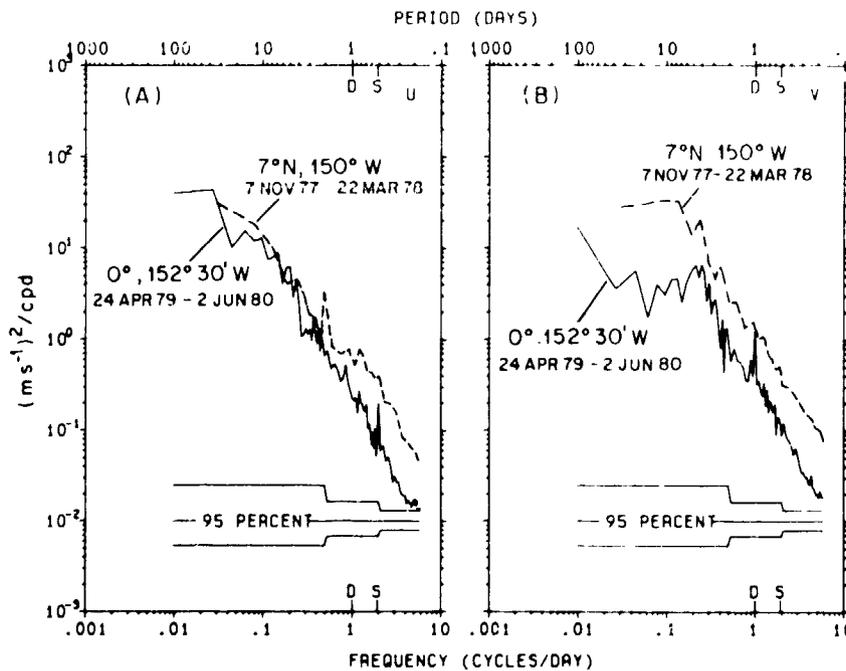
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Figure 6. Spectral estimates of (A) zonal and (B) meridional wind components at an equatorial and off-equatorial site near 150°W. The "95 percent" represents the 95% confidence level determined from the chi-square distribution and applicable to each curve.

fluctuations with a zonally-averaged rms amplitude of 0.27 m s^{-1} (Table 2). At 95°W and 109°30'W the average rms amplitude of the u component diurnal-period oscillation was 0.15 m s^{-1}. Interestingly, the wind spectra at 7°N, 150°W (Figure 6) and in the eastern Atlantic near 9°N, 23°W (Halpern, 1980) did not contain statistically significant diurnal-period spectral peaks, presumaoly because the background level of variability was considerably higher due to the nearness of the ITCZ. At 1 cpd the wind fluctuations over ~ 150 km distances near 152°30'W and 109°30'W and over 1600 km between 95°W and 109°30'W were coherent at the 95% confidence level, with magnitudes equal to or greater than the 50% noise level (Figure 5).

5.   DISCUSSION

Schemes to adequately measure the temporal and spatial variability of the surface wind field over the equatorial ocean involve the consideration of many factors, for it is not possible for a single satellite to cover completely the full spectrum of variability everywhere. For example, to sample the diurnal-period wind oscillation would require a ground track which repeated every 0.5 days or sooner; however, the equatorial distance between adjacent orbits of a single spacecraft would be nearly 5000 km (Allan, 1983), reducing the geographical coverage quite significantly. Thus, temporal repeatability, geographical coverage and the natural variability of the winds must be considered together. One compromise is a 2-day repeat cycle. This provides a Nyquist frequency of 0.25 cpd, which is the observed average frequency where the spectral slope changes to -1.25 or steeper. Except for the diurnal-period oscillations, the aliased energy folded into lower frequencies will be a small fraction of the low-frequency motions. For a 2-day repeat cycle the 1500 km nodal distance at the equator is about equal to the distance over which the diurnal-period wind oscillation was correlated, so that data from adjacent ground tracks can be used in the study of atmospheric tides. The degree to which

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the aliasing of the diurnal tidal wind fluctuation, which has an rms vector-mean speed amplitude of 0.3 m s^{-1} (or 6% of the vector-mean speed), can be reduced needs further study.

Considerable mesoscale (say, 3-30 days) variability occurs in the equatorial wind field, *e.g.*, the zonally-averaged rms amplitude of the 0.033-1.0 cpd fluctuations was 1.1 m s^{-1}. While this is nearly 30-50% of seasonal changes in the annual cycle of the wind field, it is only about 50-60% of the ±2 m s^{-1} instrumentation error expected of the satellite wind measuring systems, assuming no major improvements in sensor accuracy from the systems used on SEASAT. Thus, a new generation of satellite wind measuring sensors needs to be developed.

The distance between the satellite's ground track at the equator should be no larger than about 750 km, which is the computed (albeit from our limited data set) coherent spatial scale corresponding to our hypothetical satellite's Nyquist period for a 2-day repeat cycle.

Over the oceans the frequency-wavenumber spectrum of the surface wind field is poorly known because of the difficulty of making continuous measurements for long periods. Only accurate spacecraft sensors adequately deployed can provide the needed data. An effective design of a satellite wind measuring system must consider the observed scales of surface wind variability in the equatorial Pacific Ocean, a vast region important to global climate.

6. ACKNOWLEDGEMENTS

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