A Preliminary Evaluation of Ship Data in the Equatorial Western Pacific*

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ABSTRACT

The quality of ship data within the equatorial western Pacific is investigated using statistical analyses, and by comparison with data from neighboring island stations extracted from National Weather Service analyses. Results indicate that ship-measured sea surface temperature has an inherently small spatial scale. Surface pressure, on the other hand, has an inherently large spatial scale, which allows sparse measurements to record large-scale variations precisely. On the average, ship-measured wind, spatially averaged within a lane located near 150°E, is as good a measure of the large-scale wind flow as are the winds recorded at the sparse island stations within the western Pacific. Inaccuracies in the spatially averaged ship elements indicate that further smoothing of the data is required.

1. Introduction

The equatorial western Pacific (EWP) has become the focus of many investigations of low-frequency coupled and/or forced ocean–atmospheric phenomena; for example, teleconnection patterns, the 30–60 day oscillation, and ENSO events. Ramage (1986) suggests that off-season, near-equatorial tropical cyclone activity in the EWP generates a succession of large amplitude oceanic Kelvin waves which may be responsible for the initiation and maintenance of El Niño (Wyrtki, 1975). Several investigators (for example, Barnett, 1984) claim that the key predictor of El Niño is the zonal wind in the EWP. Madden and Julian (1971) documented a major oscillation with a period of approximately 40–50 days in the surface winds and pressures at several equatorial Pacific island stations. They found the largest amplitude of the 40–50 day cycle to be in the EWP. Thus, the importance of the EWP to the global atmospheric circulation is well established.

Many of these studies have relied on atmospheric data obtained from a few widely spaced island stations which have fairly long and complete data records. However, if relatively sparse island observations are used to describe large-scale atmosphere–ocean oscillations, it must be assumed that any temporal variations in the data are dominated by the large-scale fluctuations. Thus, it is important to know the effect of small-scale variations on the time series for various air–sea elements. (Hereafter, "large scale" and "small scale" will be used to refer to the horizontal dimensions of elements greater than and less than approximately 200 km, respectively.)

Luther and Harrison (1984) have investigated the aliasing effect of high-frequency fluctuations on the power spectrum of monthly averaged Pacific Ocean wind stress data at several Pacific island stations. They found that at least 32 randomly selected observations of wind and pressure per month (from a monthly total of 120 synoptic reports) are needed to represent the true wind stress power spectrum adequately. However, they did not investigate the relative contribution of various wavenumbers to the total variation in air–sea data.

In certain tropical regions where there are more ship observations than island stations, the former could provide a more representative estimate of large-scale variations. However, as noted by Luther and Harrison (1984) and Wright (1986), researchers have historically questioned the quality of tropical ship data. In what follows, we analyze the usefulness of shipboard measurements to investigate large-scale ocean–atmosphere phenomena in the EWP.

We have used ship observations from the heavily traveled lane along 150°E (Fig. 1) to investigate the quality and spatial characteristics of air–sea elements. Following Laing (1985), we computed cross-correlation coefficients for pairs of individual ship reports as a function of ship separation distance.

Averaging ship data over large areas successfully represents fluctuations in air–sea parameters (Wright, 1986; Wyrtki, 1975) if small-scale phenomena are unimportant. The effectiveness of spatially averaging ship data within 2° × 5° latitude–longitude boxes across the north–south shipping lane located along 150°E was

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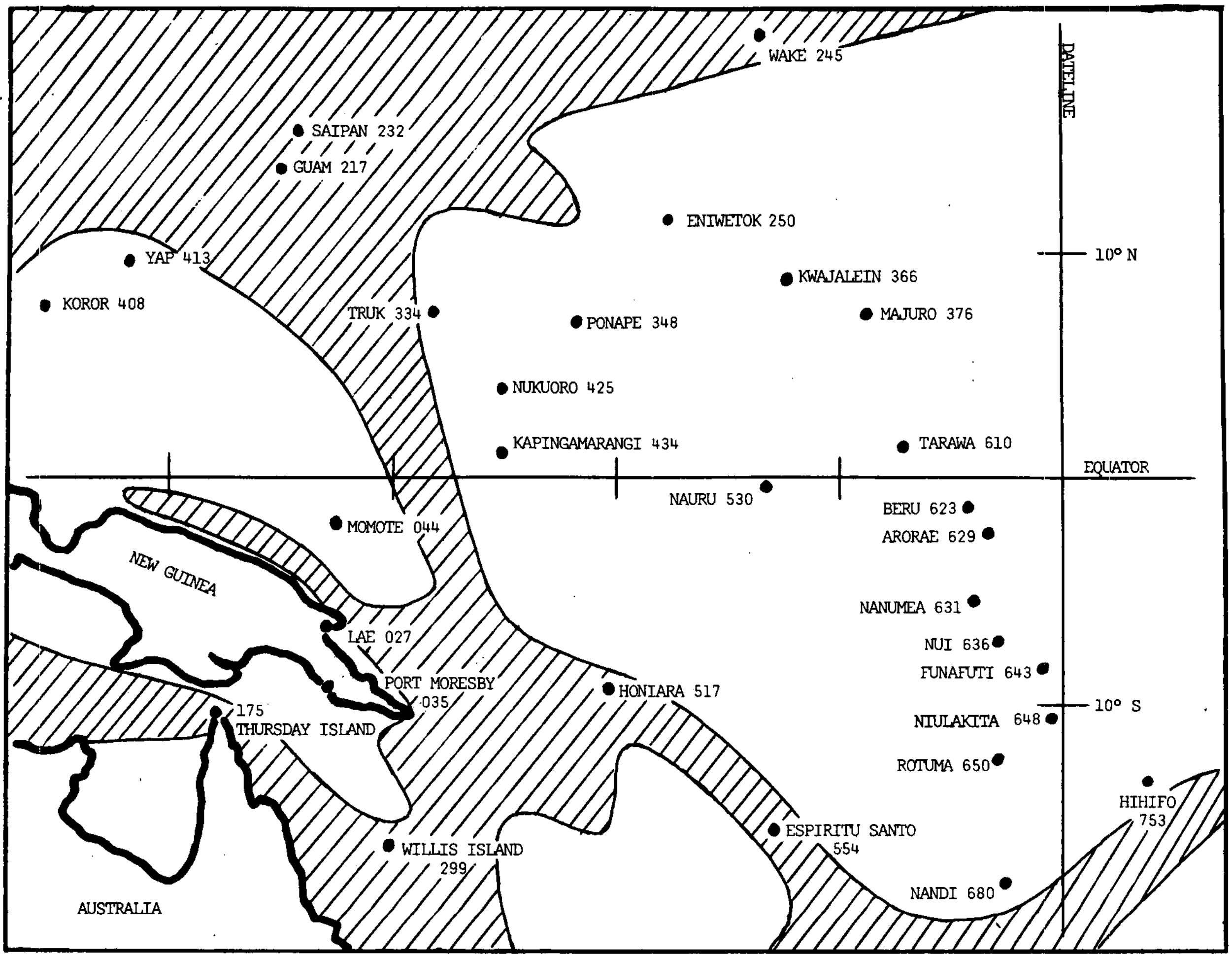

FIG. 1. Distribution of COADS ships and locations of island stations in the western Pacific. Shading indicates ship density greater than 10 per month per 2° × 2° boxes after World War II. Numbers adjacent to the islands are WMO regional station index numbers.

evaluated through comparisons with island data and statistical analyses. Simple statistical analyses determined the data density required to achieve desired accuracies.

2. Data description

Individual ship reports were extracted from the Comprehensive Ocean–Atmosphere Data Set (Woodruff et al., 1987; COADS)[1] for the period 1970–79.

Data (four times daily surface wind and pressure) for the Pacific islands Kwajalein, Majuro, Tarawa, Beru, Arorae, Nanumea, Nui, Funafuti, Niulakita and Rotuma were carefully extracted from National Weather Service surface synoptic charts for 1974. These charts facilitated visual inspection of the data for obviously erroneous station values, which, when discovered, were omitted from the record. The wind direction is plotted numerically to the nearest 10° and the wind speed is plotted to the nearest multiple of 5 kt. This introduces a round-off error of ±2 kt for each report.

Data were unevenly distributed in the EWP (Fig. 1) with ships concentrated in a north–south shipping lane along 150°E and widely scattered island stations (with a notable concentration near the dateline). The ship observational elements selected for study are sea surface temperature (SST), air temperature (AT), zonal wind (u), meridional wind (v), surface pressure (P) and total cloudiness (N). Generally, both ships and island stations observe at 0000, 0600, 1200 and 1800 UTC. Pressure data were adjusted for diurnal variation.

The selected island stations have fairly complete records (generally greater than one observation per day). However, along 150°E, ship observations within any 2° × 5° latitude–longitude box averaged 2.5 per day (Fig. 2), but with wide variations.

Earlier, we discovered numerous duplicate ship observations (Lander and Morrissey, 1987). These had slipped through COADS screening because report lo-

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[1] For more information, see the COADS Users' Manual (1985).

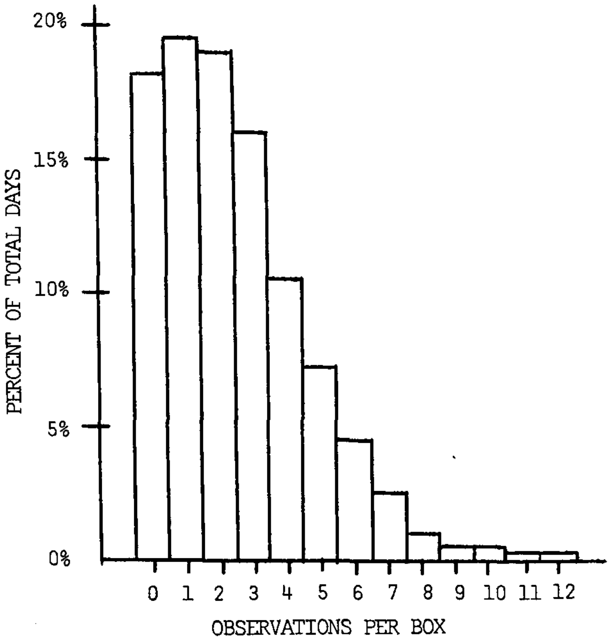

FIG. 2. Percentage of days when the given number of observations occurred in the ship boxes during the decade 1970–79.

cations differed. Also, many duplicates are not exactly the same due to round-off and transmission errors, truncations, etc. (see COADS Users' Manual, 1985). In an attempt to reduce their number we applied the fairly liberal criterion that pairs of reports identical in reporting time and identical in greater than 80% of all the reported elements were discarded. In addition to those used in this study, the elements included present weather, dewpoint depression, ship type and various cloud characteristics. Even so, some duplicate reports remain in our dataset, which the reader should remember when interpreting our results.

3. Data quality

Quality depends on observational error; we define this as the deviation of the reported value from the actual value. Observational errors are generally the result of instrument malfunctions and/or biases, observer mistakes and/or biases, transmission errors, etc. Errors in instrument calibration affect the accuracy and not necessarily the precision of a measurement. For example, a horizontal array of measurements, each with a relatively large observational error due entirely to instrument calibration settings cannot be used to indicate spatial gradients correctly, and thus cannot produce a reliable representation of the mean fields; however, it can indicate fluctuations.

Observer mistakes or transmission problems generally are responsible for random errors. Their effect can be reduced by averaging.

4. Correlation vs ship-separation distance

To assess how observational error affects the quality of ship data and to examine the spatial characteristics of the various air–sea elements in the EWP, we cross correlated pairs of individual ship reports (for each selected element) with respect to distance between ships. All unique pairs of simultaneous (reporting times match) ship reports were selected from 98 000 ship observations taken during 1970–79 in the shipping lane enclosed by 10°N to 10°S and from 140° to 160°E. Individual ships appeared to be randomly distributed within the ship track. The ship pairs were grouped at 10 km separations from 10 to 240 km and cross-correlation coefficients were then computed at each distance using simultaneous pairs. These calculations were performed for each element. In COADS, ship positions are given to the nearest 10th deg latitude/longitude, so two ships reporting the identical location and time could be approximately 15 km apart. At the smallest separation distance (0–11 km) the variance indicates how much one observation explains another one. Assuming minor gradients from 0 to 11 km, this provides a rough estimate of the observational error inherent in the measurement of each element since measurements from two collocated and properly calibrated instruments would be the same (Laing, 1985). The characteristic length scales of the various air–sea parameters can also be assessed from the variation of correlation coefficients with separation distance.

The correlations indicate that observational errors are small for u, v, and N (Figs. 3c, d, and f, respectively). Between 80% and 90% of the variance in u, v, and N measured at one ship is explained by u, v, and N measured at a collocated ship, in contrast to 60%–70% for SST, P, and AT (Figs. 3a, b, and e).

For SST, the correlation coefficient of 0.77 at the smallest separation distance indicates that the relatively low correlation coefficients for SST beyond 30 km were not due to observational error alone, but to small-scale variability. Perhaps this reflects the pattern of rainfall and/or solar radiation due to mesoscale cloudiness fluctuations together with small-amplitude, large-scale fluctuations. (We are investigating these possibilities.) Similar but smaller fluctuations affect u, v, AT, P, and N as well.

5. Correlation vs separation distance of spatially averaged data

Small-scale fluctuations account for much of the total variance in the air–sea elements. Spatial averaging would smooth out these fluctuations and also reduce the effect of randomly distributed observational errors. Some researchers have used elements observed at island stations to represent low-frequency ocean–atmosphere oscillations (Madden and Julian, 1971; Lukas et al., 1984). We now compare the performance of spatially

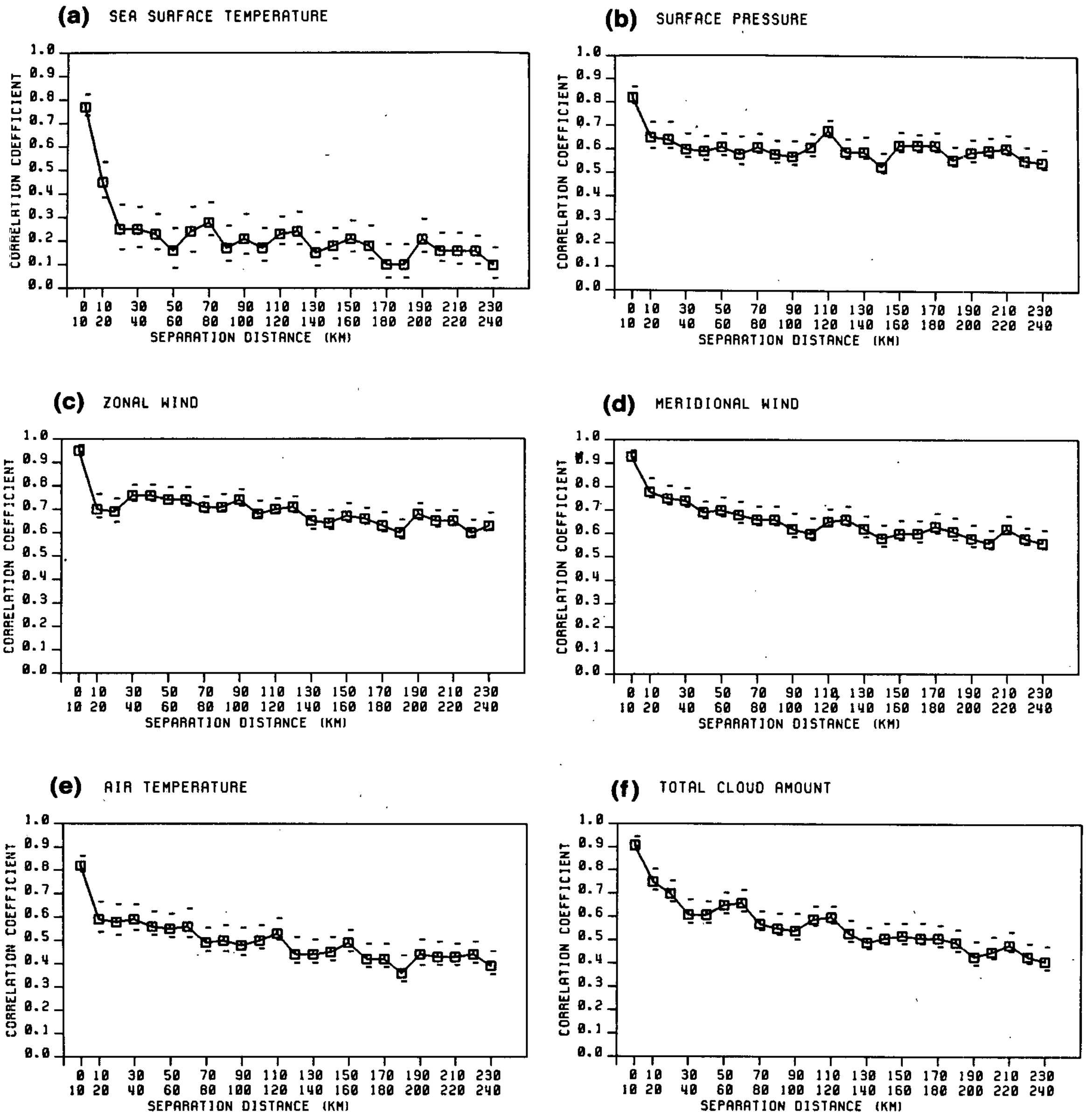

FIG. 3. Correlation vs separation distance for synoptic pairs of individual ship reports of a) sea surface temperature, b) pressure, c) zonal wind, d) meridional wind, e) air temperature, and f) total cloud. The horizontal bars represent 95% confidence limits.

averaged ship observations with observations from the sparsely distributed island stations.

Ship reports were averaged by day in 2° latitude strips across the 150°E shipping lane (5° of longitude) from 10°N to 10°S (with an average of 2.5 ships per box per day). Each pair of the ship-box daily averages for u, v and P for one year (1974) were then cross correlated with respect to box separation distance. Similar correlation computations were also performed on a north–south transect of island stations located along 170°E (Fig. 1).

In comparing ship and island correlation coefficients, curves were fitted to the computed data as follows: an exponential curve of the form $f(x) = A^{-Bx}$ for u; a second-order polynomial of the form $f(x) = C + Dx + Ex^2$ for v; and a third-order polynomial of the form $f(x) = F + Gx + Hx^2 + Ix^3$ for P (where A, B, C, D, E, F, G, H, and I are coefficients determined from a least-squares method and x is the separation distance in degrees of latitude; see Figs. 4, 5, and 6). These models were initially chosen based on a subjective assessment of the data distribution. The curves were fit to facilitate comparisons only.

For island and ship-box u, a least-squares fit minimized the error $e^2 = \sum (\ln(f(x_i)) + Bx_i - \ln(A))^2$. All coefficients were significantly different from zero at the

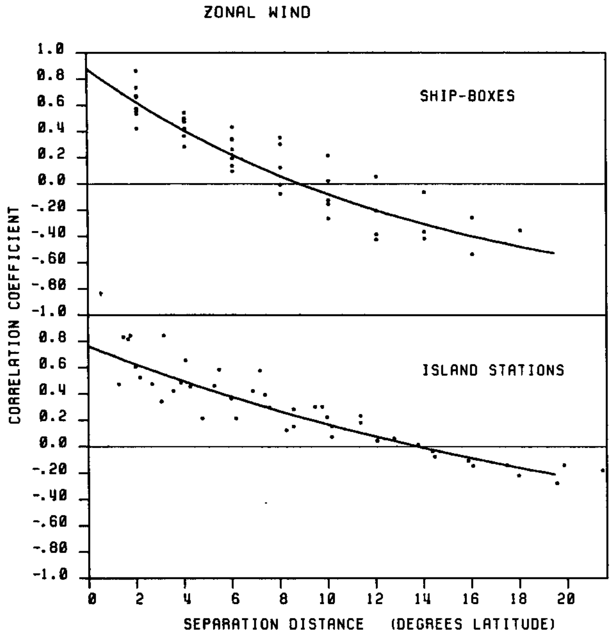

FIG. 4. Correlation coefficients vs separation distance for each synoptic pair of observations of zonal wind from (top) ship boxes and (bottom) island transect. Solid lines are curves fitted to the data.

95% confidence limit. Partial F tests (Montgomery and Peck, 1982) confirmed that the exponential curve provides an adequate fit to the correlation coefficients; higher-order polynomials do not significantly add to the description of the data.

For v, a partial F test indicated that the second-order polynomial was the minimum ordered polynomial necessary to describe the data. However, for P, partial F tests and residual analyses determined that the third-order polynomial significantly improved the data description over lesser-order polynomials. That similar curves fit similar parameters indicates no major differences between the ship and island transects in the meridional structure of wind and pressure.

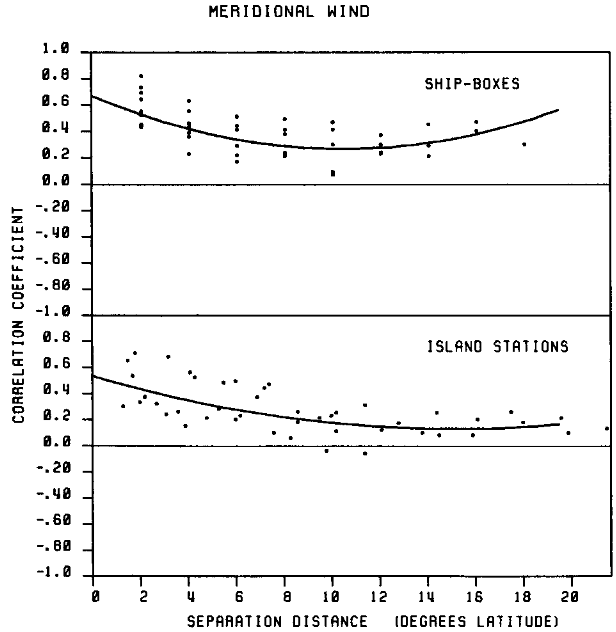

FIG. 5. As in Fig. 4 except for meridional wind.

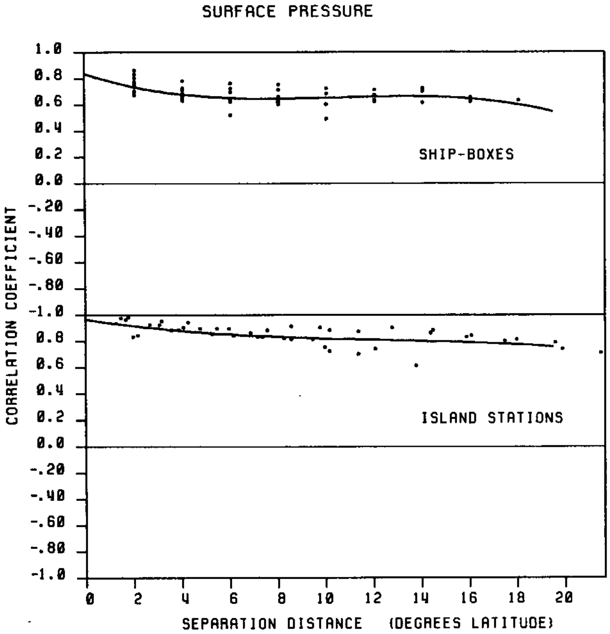

FIG. 6. As in Fig. 4 except for surface pressure.

The characteristic meridional length scales of zonal wind (u) differ (Fig. 4). This is indicated by the separation distance at which the fitted curves cross the abscissa: 9.0° for the ships and 13.8° for the islands.

The island v and the ship-box v yield similar distributions of correlation coefficients with respect to separation distance (Fig. 5). However, as with u, ship-box v has a different meridional length scale. This is evident by the stronger curvature of the second-order curve for the ship boxes and the smaller separation distance at which the ship-box curve reaches a minimum (11.1° for ship boxes and 16.2° for islands). However, contrary to u, the correlation values at all ship-box separation distances are larger than those of the islands. This indicates that overall the spatially averaged wind from these ship boxes is about as good a measure of the large-scale wind flow as are the island station winds.

The distributions of correlation coefficients of P with respect to separation distance are quite similar for both ship boxes and islands (Fig. 6), suggesting little structural difference in the large-scale pressure variations. The island correlation coefficients are consistently higher at each separation distance, indicating greater spatial coherency. Since the spatial resolution of ship observations is generally higher than the island stations, we suspect that different barometric calibrations among different ships account for the relatively lower correlation coefficients. (Note that island pressure readings may also be affected by calibration errors; however, because the islands are stationary, the correlations are not influenced by these errors.) At small separations (less than 2°), island correlation coefficients are near 0.95. Island and ship correlation coefficients remain high at large separations (islands correlate at greater than 0.80 even at 20° separation; 10°N compared with 10°S). This suggests that pressure fluctuations in the EWP are dominated by very large horizontal scales.

That small-scale pressure fluctuations contribute little to the total pressure variation indicates that these island stations can accurately measure large-scale pressure changes in the EWP. However, since the horizontal pressure gradients in the EWP are generally very small (often 1 mb per 1000 km), small calibration errors at island stations could make an accurate synoptic isobaric analysis difficult.

6. Spatial coherence of surface pressure

The strong coherence over 20° of latitude probably stems from an equally large-scale physical mechanism. The 40–50 day oscillations (Madden and Julian, 1972) are on a global scale with wavenumber 1 and may contribute to the spatial coherence of surface pressure. After band-pass filtering, the recomputed cross-correlation coefficients for the filtered data were high with separation distance (Fig. 7). However, correlation coefficients remained nearly as high even without the 40–50 day cycles. Individual time series for each island station (not shown) reveal that all fluctuations down to a few days are coherent for the entire transect. Frolow (1942) first investigated large-scale simultaneous pressure fluctuations using Atlantic and Caribbean island data. Palmer and Ohmstede (1956) and Brier and Simpson (1968) observed similar Pacific-wide fluctuations and noted that they are usually on the order of 1 to 3 mb per day. Madden (1979) showed evidence of global-scale, 5-day traveling pressure waves. He suggested that these waves have characteristics similar to large-scale Rossby waves. The mechanism responsible for this is being investigated.

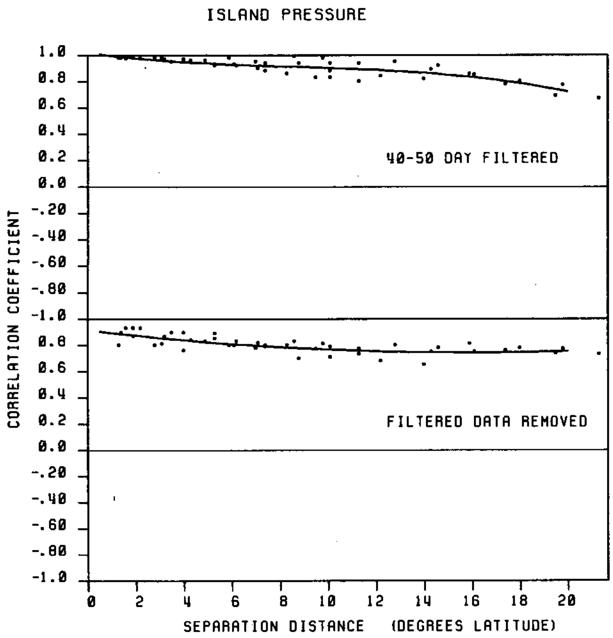

FIG. 7. As in Fig. 4 except for island pressure data; 40–50 days filtered and with the filtered data removed.

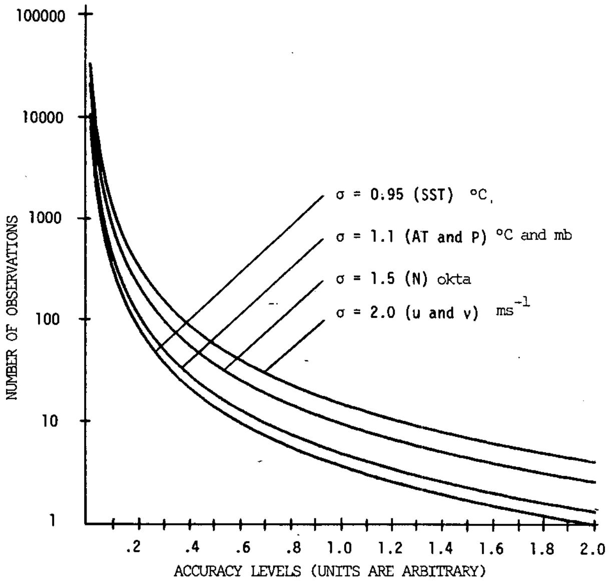

FIG. 8. Number of ship observations required in 2° × 5° box to obtain a desired accuracy given the population standard deviation for a particular parameter. Curves for computed population standard deviations of SST, AT, *P*, *N*, *u*, and *v* are shown.

7. Accuracy as a function of the density of ship observations

The more observations that go into the spatial average, the closer the computed average will be to the true value. How close the average is to the true value or the "accuracy" of the sample determines the usefulness of the data. The number of ship observations needed to make spatial averages of a desired accuracy can be obtained by using the central limit theorem (DeGroot, 1986). It states that sample means $\bar{x}_i$ of a random sample of size n taken from any distribution with mean μ and variance σ^2 will be approximately normally distributed with mean μ and variance σ^2/n. Thus,

$$\Pr(|\bar{x} - \mu| \leq \text{Ac}) = \Pr[|Z| \leq (\text{Ac})(n)^{1/2}/\sigma] \quad (1)$$

and

$$Z = |\bar{x} - \mu|/(\sigma^2/n)^{1/2} \quad (2)$$

where Ac is the desired accuracy and Z is the standard normal variate. Therefore, at the 95% confidence limit,

$$\Pr[|Z| \leqslant (\mathrm{Ac})(n)^{1/2}/\sigma] \geqslant 0.95. \qquad (3)$$

Equation (3) yields an expression for the minimum number of observations required to obtain the desired accuracy (Ac),

$$n \geqslant [(1.96\sigma)/\mathrm{Ac}]^2. \qquad (4)$$

Thus, the population standard deviation (σ) can relate the number of observations to the prespecified accuracy provided it varies little from day to day.

For each element, sample spatial standard deviation values are determined per box per day for boxes having at least four observations per day. These values are then averaged for the 10-yr period (1970–79) to provide population standard deviations (Fig. 8). For example, if an accuracy of 1° centigrade is desired for box-averaged SST, then on the average, four or more observations per box per day are required.

Accuracies corresponding to the mean number of observations per box per day for the 10-yr period (2.5) are given in Table 1, column 2.

The average of the daily differences between adjacent boxes for the 10-yr period (column 3), as well as the average of the day-to-day variations in each box element (column 4) differ only slightly from the values in column 2. Thus, in order to assess the gradients of the box elements at these time and space scales, further smoothing of the box averages (temporal, spatial, or a combination of both) is required. Through subjective spatial–temporal smoothing of the zonal wind (Fig. 9), useful information could be extracted, such as the occurrence, strength and duration of westerly wind along the ship track.

8. Summary

The relative magnitude of the observational errors associated with shipboard measurements of wind and cloud was found to be quite small in comparison to SST, AT, and P. Within the EWP, the significant decrease in correlation coefficients from 0 to 30 km separation distance indicates that SST has a inherently small spatial scale (<30 km), possibly in response to mesoscale variations in cloudiness and/or rainfall. Instrument error by itself cannot account for the rapid decrease in correlation with distance, unless this error is a function of separation distance. Thus, detailing day-to-day variations in large-scale SST demands a dense observational array.

On the average, ship-box winds within the ship track measure the large-scale EWP flow as well as the extracted island winds.

Both ship and island meridional transects indicate that surface pressure within the EWP has an inherently

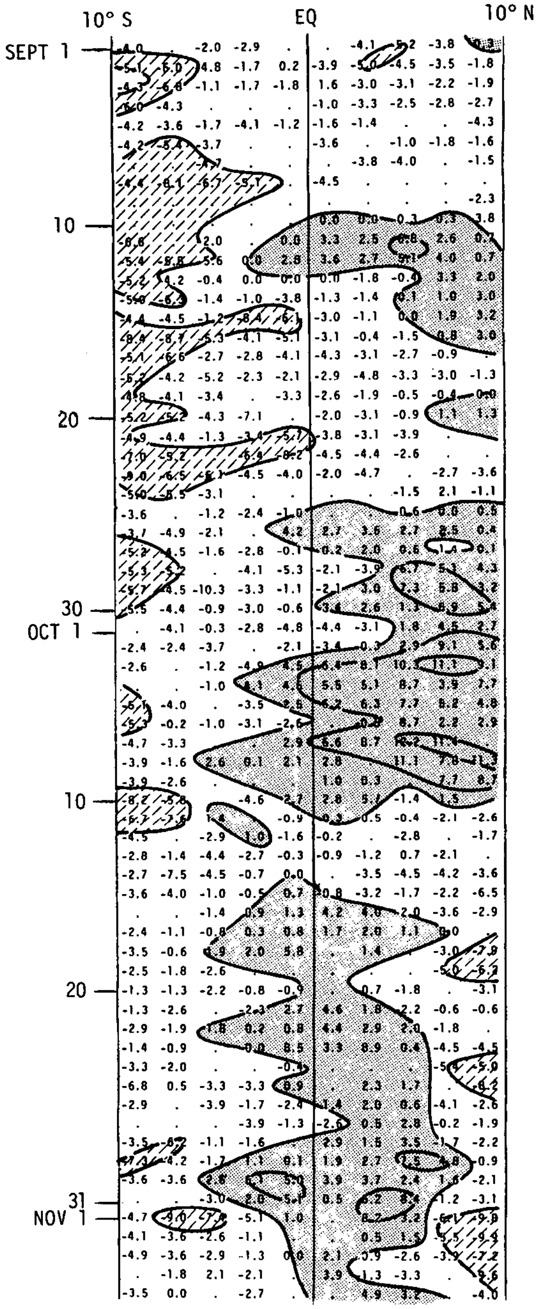

FIG. 9. Transect of daily averaged zonal wind using the 2° × 5° ship boxes along the shipping lane at 150°E. Shaded regions indicate westerly winds and dashed regions indicate easterly winds ≥ 5 m s⁻¹.

TABLE 1. Computed accuracies vs box-to-box gradients.

Variable	Accuracies (n = 2.5)	Mean difference between adjacent boxes	Mean day-to-day variation
SST	1.1°C	0.8°C	1.0°C
P	1.3 mb	1.1 mb	1.2 mb
u, v	2.5 m s^{-1}	1.9 m s^{-1}	2.17 m s^{-1}
AT	1.3°C	1.0°C	1.3°C
N	1.8 oktas	1.6 oktas	1.8 oktas

large spatial scale (much greater than 20° latitude). Thus, sparse island stations precisely record large-scale pressure variations. Ship-box pressure averages apparently suffer from errors introduced by differing shipboard calibration.

The strong spatial coherency of pressure fluctuations at 40–50 day periods, and with this frequency band removed, is a curious phenomenon which warrants further research.

Our investigations showed that inaccuracies in the ship-box air–sea elements require that the daily ship-box estimates undergo further spatial and/or temporal smoothing.

This study represents the first step towards our larger goal of completing an extensive evaluation of the COADS.

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