# Tropical Wind Stress from Time-Averaged Winds*

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ABSTRACT

Oceanwide direct measurement of the surface wind stress is impracticable; instead, the wind stress must be parameterized in terms of individual shipboard wind reports. The number of ship observations, however, are insufficient over the tropical oceans for an adequate analysis of the wind stress. A method is developed to take advantage of the monthly mean wind field which can be determined by meshing several sources of data with the ship observations. It is shown that a single empirical correction factor can be used to estimate the surface pseudostress from monthly mean winds for all months throughout the oceanic tropics.

## 1. Introduction

The increasing interest in climate analysis and forecasting has demanded better wind stress data to test numerical models of the coupled ocean–atmosphere. What is now viewed as the dominant role of the tropical oceans in climate variability has emphasized the importance of tropical wind stress; its determination is a major problem of the Tropical Ocean Global Atmosphere (TOGA) international research program (WMO 1985). Since few direct stress measurements are available, large-scale studies customarily parameterize the stress in terms of conventional shipboard wind measurements using a bulk equation of the form

$$\tau = \rho C_d |\mathbf{V}| \mathbf{V} \qquad (1)$$

where $\tau$ is the surface wind stress, $\rho$ is the atmospheric density, $C_d$ is a drag coefficient, and $\mathbf{V}$ is the surface wind vector. The drag coefficient is usually treated as some function of $\mathbf{V}$.

Over the tropical oceans, ships are the primary source of surface wind observations. The accuracy and reliability of ship wind observations has been questioned (Bunker 1976; Wright 1986; Ramage 1984). Morrissey et al. (1988) conclude that suitable averaging of ship winds can improve the quality of the wind estimates. Over most of the tropics, however, ship observations are too sparse to determine an accurate time average on a monthly or even longer scale. Fortunately, on monthly or longer time scales a reasonable surface wind field can be determined by using averaged auxiliary data such as satellite winds, satellite observed cloudiness, atoll and small island wind observations, and climatology. Wind vectors obtained from the motion of the low-level clouds are a major dataset which can substantially add to the information available from ships. Sadler and Kilonsky (1985) developed a method of estimating monthly mean surface winds from monthly mean satellite winds. Thus, a monthly mean surface wind product is available without a corresponding set of surface stress products.

The same problem arises in midlatitudes if, say, monthly mean surface pressure is available but not the surface stress. The pressure field can be used to deduce a surface wind field and this may be converted to a surface stress. In order to solve the problem, Wright and Thompson (1983) developed a formula based on the assumption that departures from the monthly mean wind have a simple circularly symmetric form of probability density function. An approximate formula that expresses the relationship between the mean wind $\mathbf{V}_0$ and the mean stress $\tau_0$ is

$$\tau_0 = \rho C_d(\alpha)\alpha \mathbf{V}_0. \qquad (2)$$

This would be identical to Eq. (1) if $\alpha$ were the wind speed $s = |\mathbf{V}_0|$, but where $\mathbf{V}_0$ and $\tau_0$ are monthly mean values, the quantity $\alpha$ is given by

$$\alpha^2 = s^2 + 4\sigma^2 \qquad (3)$$

where $s = |\mathbf{V}_0|$ is the monthly mean wind speed and $\sigma$ is the standard deviation of the wind components.

Often, a quantity called pseudostress is used as a substitute for stress because of uncertainties in the functional form of the drag coefficient. The pseudo-

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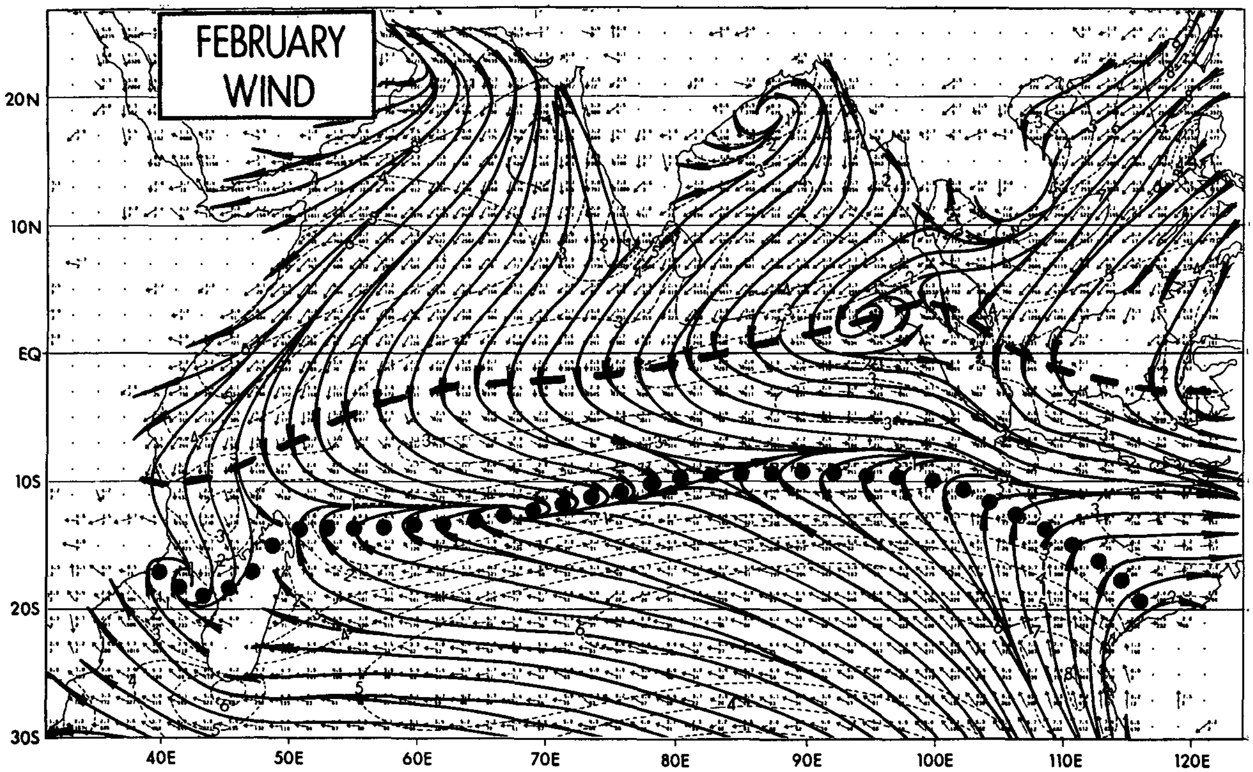


FIG. 1. Streamline analysis of February long-term (1900–1979) monthly mean ship winds in the Indian Ocean. Monsoon trough position is shown by dotted line and buffer system by heavy dashed line. Data source: COADS.

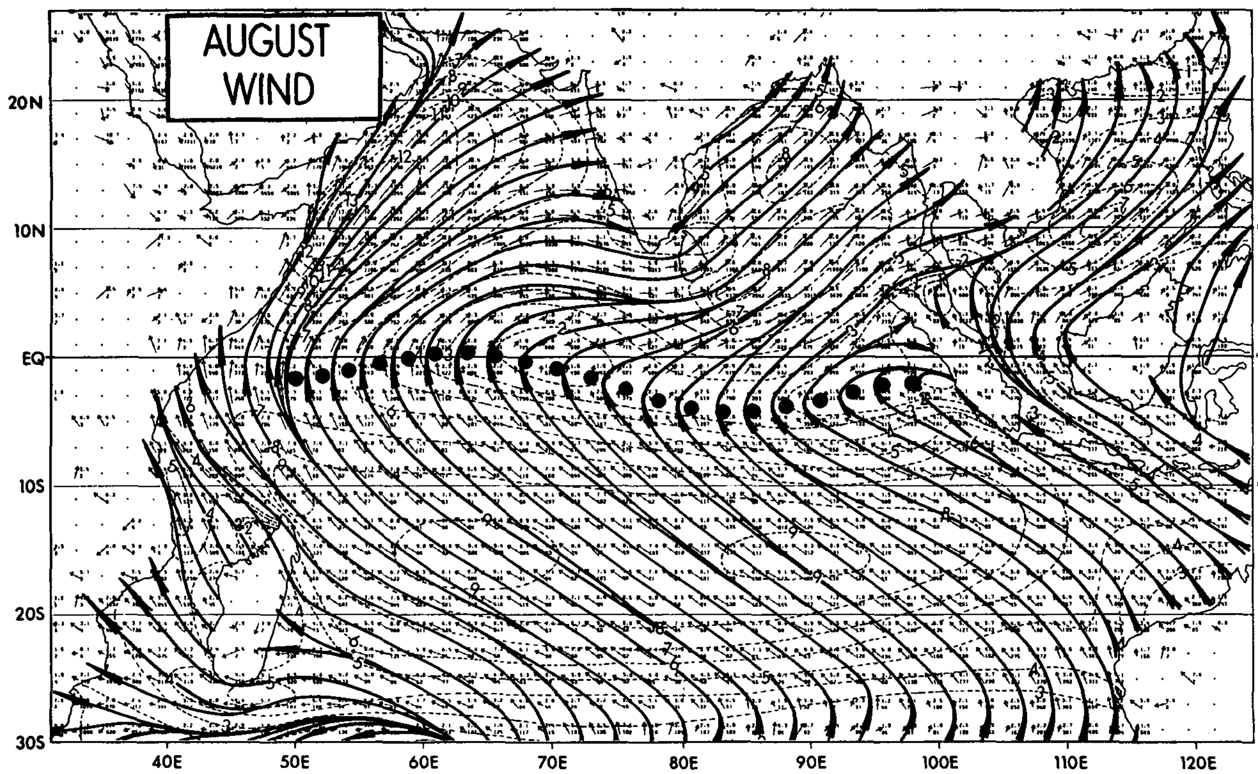


FIG. 2. Streamline analysis of August long-term (1900–1979) monthly mean ship winds in the Indian Ocean. Axis of buffer system is indicated by dotted line. Data source: COADS.

stress is defined as $\mathbf{P} = |\mathbf{V}|\mathbf{V}$ for any given wind observation. The mean value $\mathbf{P}_0$ is related to $\mathbf{V}_0$ by

$$\mathbf{P}_0 = \alpha \mathbf{V}_0 \tag{4}$$

where $\alpha$ may be given by Eq. (3). Thus, all that is needed for conversion of monthly mean surface wind to monthly mean pseudostress is knowledge of $\sigma$. Thompson et al. (1983) find from some tests at midlatitude weather ships that climatological values of $\sigma$ could be used without introducing large errors.

This paper concerns our efforts to find values for $\alpha$ that can be used in the oceanic tropics to determine accurately the monthly mean pseudostress from the monthly averaged surface wind prepared from ship observations and the aforementioned auxiliary sources. We determine $\alpha$ empirically using the Comprehensive Ocean Atmosphere Data Set (COADS). The COADS (Woodruff et al. 1985) is a compilation of global ship observations from 1854–1979 that also includes computations of the surface pseudostress and standard deviations of the horizontal wind components. The COADS long-term mean pseudostress is computed as the average of the squares of the individual ship wind reports. This is equivalent to $\mathbf{P}_0$ in Eq. (4). Long-term monthly means of COADS ship winds were obtained from Sadler et al. (1987). Thus $\mathbf{P}_0$ and $\mathbf{V}_0$ are known for the tropical oceans. A formula for $\alpha$ was determined from the properties of the ratio $|\mathbf{V}_0|^2/|\mathbf{P}_0|$. One simple

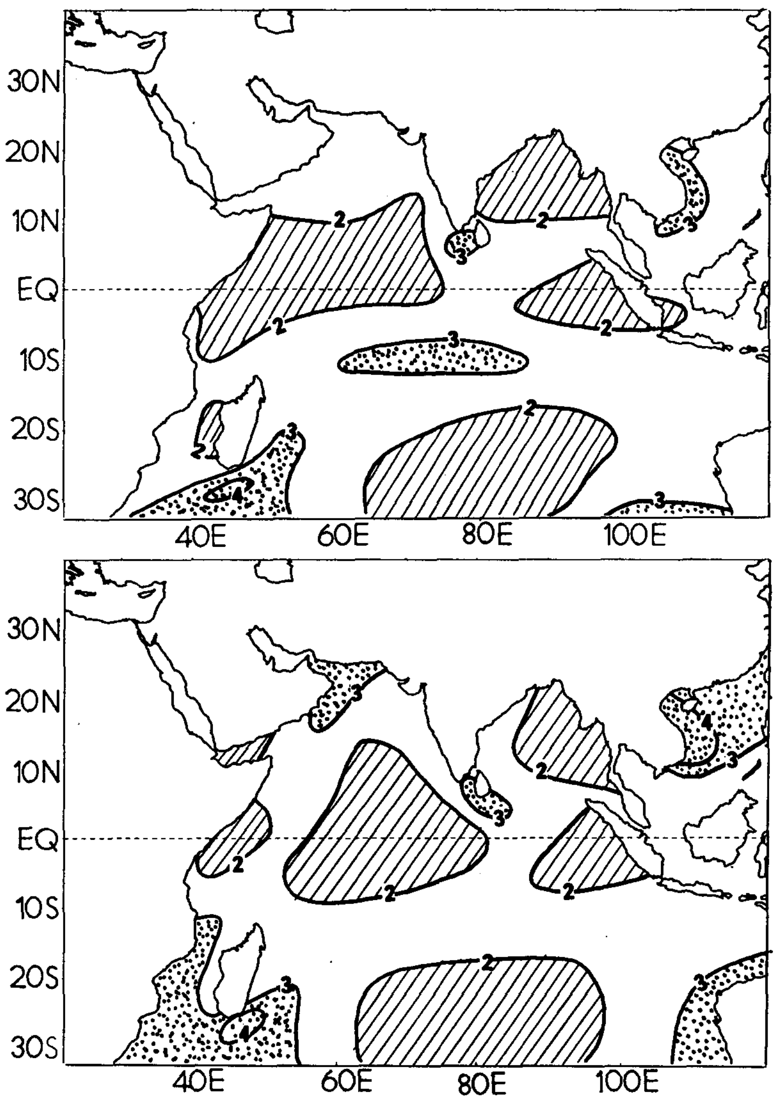


FIG. 3. Standard deviations of the (a) zonal and (b) meridional components of the wind during February. Stippled regions are greater than 3 m s$^{-1}$; hatched regions are less than 2 m s$^{-1}$.

formula for $\alpha$ was found to be applicable throughout the tropics at any time. Thus, the tropical monthly mean pseudostress $\mathbf{P}_0$ may be produced given only the monthly mean wind $\mathbf{V}_0$.

## 2. The variance of tropical winds

Of the analyses made for all months over the three oceans (Sadler et al. 1987), we selected for demonstration, February and August in the Indian Ocean where the annual cycle in the wind circulations (monsoons) is largest. In February (Fig. 1) the monsoon trough spans the South Indian Ocean and the mean speed of the monsoon westerlies barely exceeds 3 m $s^{-1}$. The Northern Hemisphere (NH) northeast flow has core speeds of 7, 6, and 4 m $s^{-1}$ in the South China Sea, Arabian Sea, and Bay of Bengal, respectively. The Southern Hemisphere (SH) southeast trades exceed 8 m $s^{-1}$ off Australia and decrease westward to about 5 m $s^{-1}$ in the western Indian Ocean. Light winds are associated with the monsoon trough, buffer system and the small anticyclones in the northwest corners of the Bay of Bengal and the Arabian Sea. In August (Fig. 2) the monsoon trough is north of 20°N and mostly over land; the buffer system is just south of the equator. The monsoon westerlies have core speeds of 13, 8, and 7 m $s^{-1}$ in the Arabian Sea, Bay of Bengal, and South China Sea, respectively. The SH southeast trades exceed 9 m $s^{-1}$ in two core areas across the Indian Ocean and in an orographically enhanced area off the north tip of

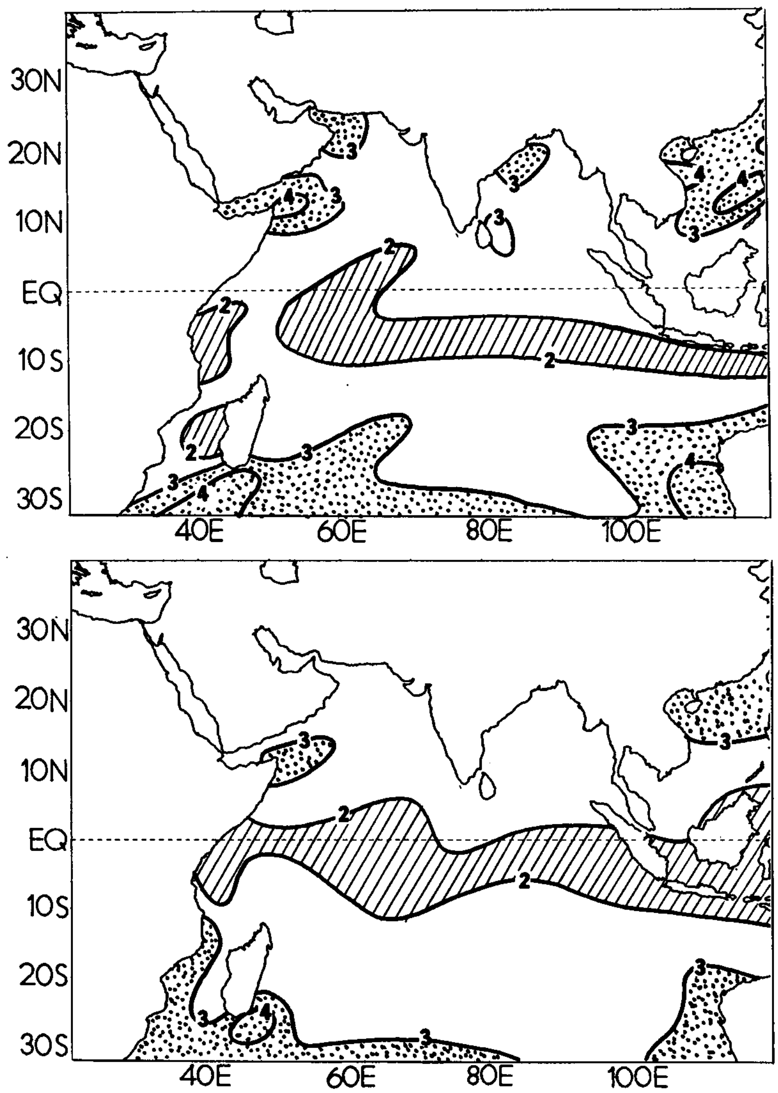


FIG. 4. Standard deviations of the (a) zonal and (b) meridional components of the wind during August in the Indian Ocean. Stippled regions are greater than 3 m $s^{-1}$; hatched regions are less than 2 m $s^{-1}$.

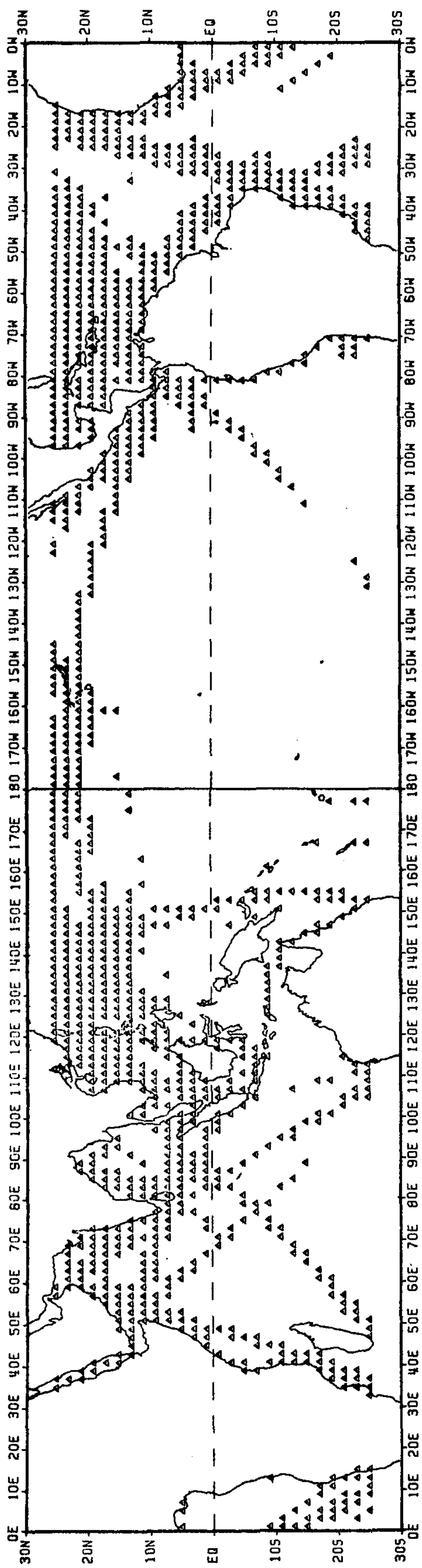

FIG. 5. Typical distribution of 2° lat by 2° long grid squares between 25°N and 25°S which contain 300 or more ship observations for the long-term (1900–1979) monthly averages.

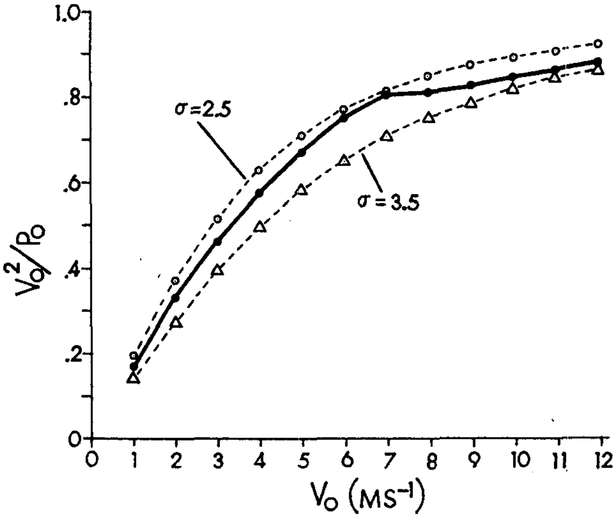


FIG. 6. Ratio of the square of the mean wind ($|\mathbf{V}_0|^2$) to the mean of the squared wind ($\mathbf{P}_0$) as a function of the mean wind ($|\mathbf{V}_0|$). Solid line is our empirically derived curve for the tropical oceanic regions. Dashed lines indicate computed ratios using Wright and Thompson's formula [Eq. (3)] for $\sigma = 2.5$ m s$^{-1}$ (small open circles) and for $\sigma = 3.5$ m s$^{-1}$ (open triangles).

Madagascar. Minimum speeds are associated with the buffer systems and the SH subtropical ridge near 30°S. Both months show numerous orographically induced smaller scale minima and maxima.

The highly structured patterns in the wind speed fields (Figs. 1 and 2) have no counterpart in the fields of standard deviations (Figs. 3 and 4). In the open seas in February the standard deviations of both the zonal and meridional wind varies between about 1.5 and 2.5 m s$^{-1}$ and exceeds 3 m s$^{-1}$ only near the monsoon trough. The August standard deviations of the wind components are near 2.5 m s$^{-1}$ over most of the open ocean. Larger standard deviations are associated with the higher latitude winter westerlies. Tropical standard deviations of over 3 m s$^{-1}$ are associated with the very high wind speeds and strong wind gradients in the western Arabian Sea. Some of this is due to orographic enhancement while some stems from comparing observations across an intense gradient; for example, there is a 7.9 m s$^{-1}$ difference in the mean wind speed between two adjacent 2° latitude by 2° longitude boxes off the northeast tip of Africa.

Thus, over the tropics the wind variance is relatively small and almost constant in space and time. Therefore, perhaps variations in space and time of the standard deviations of the wind components in the tropics can be ignored and a single specification for $\alpha$ may suffice for all regions of the tropics for all months.

## 3. Empirical relationships between the monthly mean pseudostress and the monthly mean wind

Initially we used data from every 2° latitude by 2° longitude box between 30°N and 30°S that contained

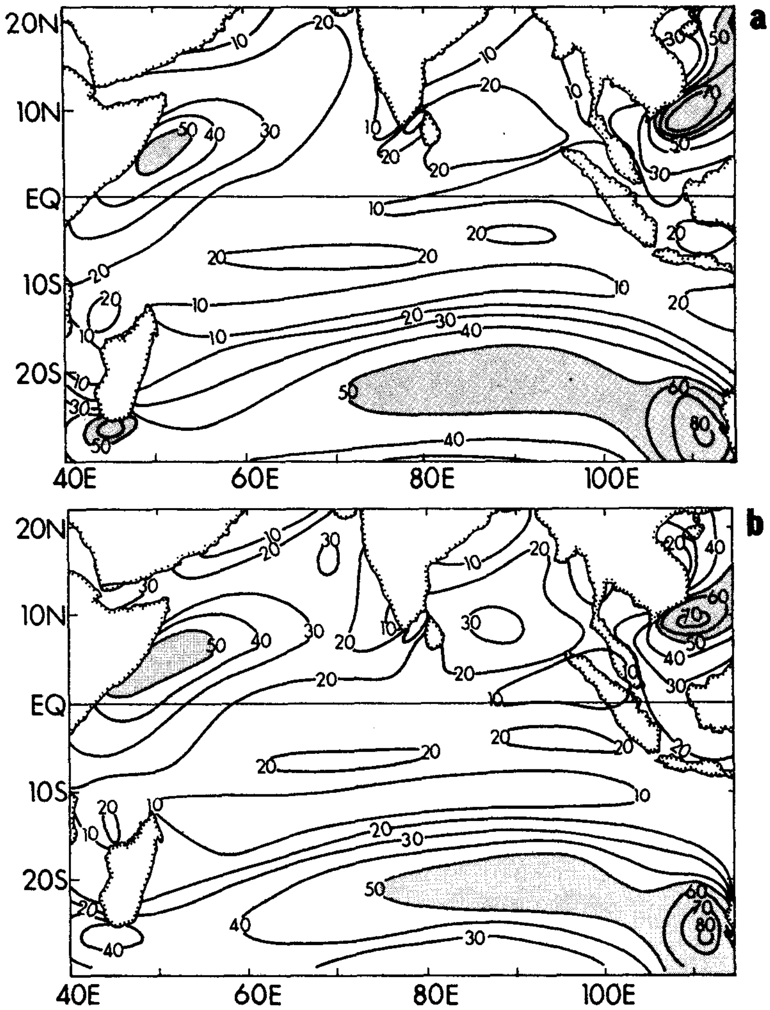


FIG. 7. Analyses of the magnitude ($m^2 s^{-2}$) of the February monthly mean pseudostress: (a) computed properly as the mean of the squares of the individual wind observations (an element included in the COADS) and (b) computed using Eq. (4) with $\alpha$ given by our empirical formula, Eq. (8). Shaded regions indicate magnitudes of 50 $m^2 s^{-2}$ or greater. Orientation of the pseudostress vectors is parallel to the wind shown in Fig. 1.

300 or more observations per 80-year per month and compared the averaged wind speed and the averaged pseudostress for each month (Sadler et al. 1986). Computations indicated biasing in the NH winter months when numerous observations fall in the higher latitudes of the North Pacific and North Atlantic where midlatitude systems penetrate further equatorward in winter than in summer. The data poleward of 26° were therefore eliminated to reduce the midlatitude contamination; a typical monthly distribution of the remaining 2° by 2° boxes is shown in Fig. 5.

Various regression curves were fitted to the data with the monthly mean wind speed ($|\mathbf{V}_0|$) as the independent variable and the percentage ($\Pi$) of the mean wind squared ($|\mathbf{V}_0|^2$) to the mean of the squared wind ($\mathbf{P}_0$) as the dependent variable (see Sadler et al. 1986). Each was tested by comparing analyzed monthly fields of COADS long term monthly mean pseudostress with the corresponding pseudostress computed from the regression equations. Because of the uniformity in time and space of the standard deviations of the zonal and meridional wind components in the tropics (Figs. 3 and 4), we also compared results using the combined dataset for all 12 months. The final selected relationship

$$\Pi = -0.02 + 18.28\,|\mathbf{V}_0| - 0.97\,|\mathbf{V}_0|^2; \quad |\mathbf{V}_0| < 7 \text{ m s}^{-1} \tag{5}$$

$$\Pi = 65.97 + 1.88\,|\mathbf{V}_0|; \quad |\mathbf{V}_0| \geqslant 7 \text{ m s}^{-1} \tag{6}$$

$$\Pi = 1.00; \quad |\mathbf{V}_0| \geqslant 18 \text{ m s}^{-1} \tag{7}$$

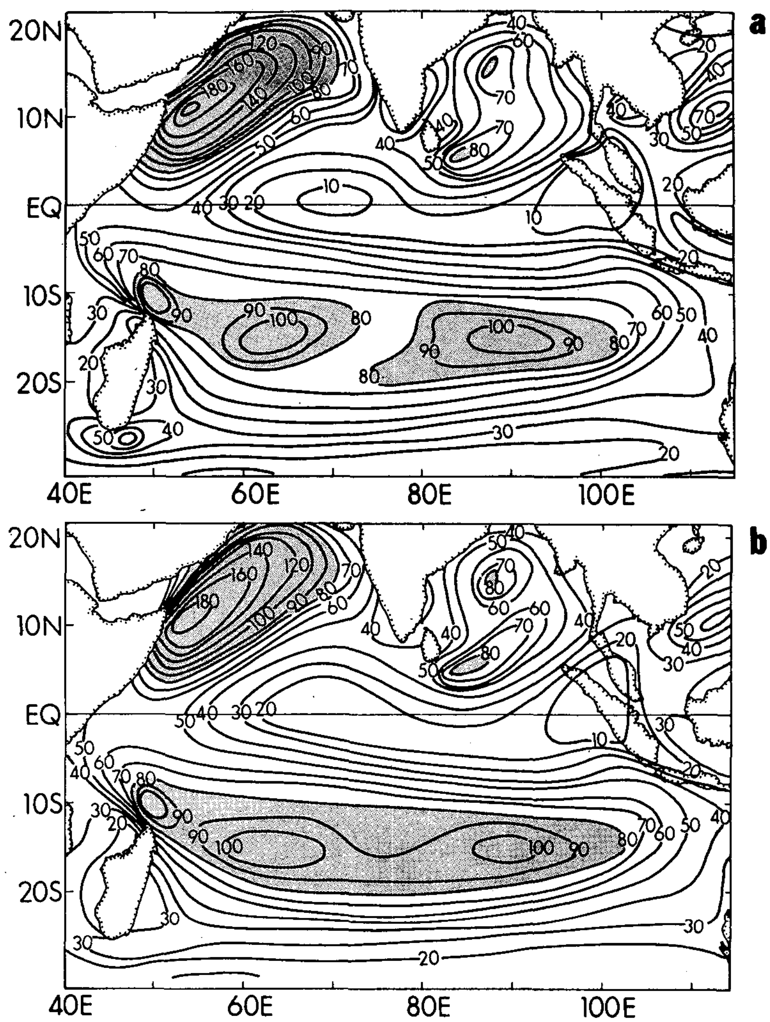


FIG. 8. Analyses of the magnitude ($m^2 s^{-2}$) of the August monthly mean pseudostress in the Indian Ocean: (a) computed properly as the mean of the squares of the individual wind observations (an element included in the COADS) and (b) computed using Eq. (4) with $\alpha$ given by our empirical formula, Eq. (8). Shaded regions indicate magnitudes of 80 $m^2 s^{-2}$ or greater. Orientation of the pseudostress vectors is parallel to the wind shown in Fig. 2.

was derived from the combined dataset. The value of the multiplying factor $\alpha$ to be used in Eq. (4) is now

$$\alpha = 100|\mathbf{V}_0|\Pi^{-1}. \tag{8}$$

Equations (5), (6), and (7) yield values for $\alpha$ that are within the range of values for $\alpha$ in the tropics determined by Gill (1985). Inserting typical values of the standard deviations of the wind components in the tropics into Wright and Thompson's (1983) formula for $\alpha$ [Eq. (3)] yields values that are close to ours (Fig. 6). A small increase in the standard deviations at higher wind speeds ($>6$ m $s^{-1}$) is suggested by the position of our curve with respect to those of Wright and Thompson. The spatial distribution of biases resulting from the use of our 12-month averaged correction factor [Eq. (8)] is discussed in the next section.

## 4. Comparisons of COADS pseudostress with pseudostress computed from averaged winds

The pseudostress as computed from individual winds and as computed from averaged winds using Eq. (4) [with values for $\alpha$ specified by Eqs. (5), (6), and (7)] agrees to within 10% for all tropical regions between 25°N to 25°S for all months (see Figs. 7 and 8). Largest differences occur in small coastal areas which experience the largest wind variance; the best example is off the coast of Madagascar. The pseudostress computed from Eq. (4) using $\alpha$ given by Eq. (8) has a low bias in the small and scattered high-variance areas and a small high bias over most of the rest of the tropical oceans.

## 5. A test of the empirical relationships on an independent dataset

Ship reports from an interim COADS update for the period January 1980 through December 1985 were used for a test on an independent dataset. Because of an abundance of data, we chose the South China Sea as the test region. The pseudostress was computed within each 2.5° latitude by 2.5° longitude box (containing five or more observations per month) in the following ways: (i) as the mean of the squares of each individual wind observation (the "true" pseudostress, $\mathbf{P}_0$), and (ii) as the square of the monthly mean wind within each box multiplied by our empirically determined $\alpha$.

Multiplying $\mathbf{V}_0$ by $\alpha$ provides an accurate estimate of the "true" pseudostress (Fig. 9a). Simply squaring the mean wind produces an estimate of the pseudostress that falls substantially short of the "true" pseudostress (Fig. 9b).

## 6. Converting pseudostress to stress

Ocean currents are driven primarily by the surface wind stress, $\tau$. In order to convert the pseudostress ($\mathbf{P}$) to stress ($\tau$), it must be multiplied by a drag coefficient. There are several proposed forms for the functional dependence of the drag coefficient ($C_d$) on the surface wind speed ($|\mathbf{V}|$); e.g., Garratt (1977), Large (1979), Wu (1980), and Smith (1980). If values of the pseudostress are provided to oceanographers, they are free to apply their choice of drag coefficient.

In this paper we showed how the monthly averaged pseudostress ($\mathbf{P}_0$) could be obtained for the oceanic tropics given only the monthly mean wind ($\mathbf{V}_0$). If the drag coefficient is constant, then the monthly averaged surface wind stress ($\tau_0$) may be obtained as

$$\tau_0 = \rho C_d \mathbf{P}_0. \tag{9}$$

If the drag coefficient increases with increasing wind speed, then the quantity $\rho C_d(\mathbf{V}_0)\mathbf{P}_0$ will underestimate $\tau_0$. The relative magnitude of the underestimate is a function of both the rate of increase of $C_d$ and the variance of the components of the individual wind observations comprising $\mathbf{V}_0$. A rigorous mathematical exploration of the effect of a variable drag coefficient on the estimate of $\tau_0$ from $\mathbf{P}_0$ is beyond the scope of this paper, but a simple example has been worked out which gives some indication of the effect: given that

$$C_d(|\mathbf{V}|) = 0.001(0.75 + 0.067|\mathbf{V}|) \tag{10}$$

(after Garratt 1977) and that the standard deviation of the wind components of the individual wind observations comprising $\mathbf{V}_0$ is a typical tropical value (say, 2.5 m s$^{-1}$); then, for low monthly averaged wind speeds (0–4 m s$^{-1}$), the quantity $\rho C_d(\mathbf{V}_0)\mathbf{P}_0$ underestimates $\tau_0$ by more than 10%. For higher wind speeds, the relative magnitude of the underestimate decreases.

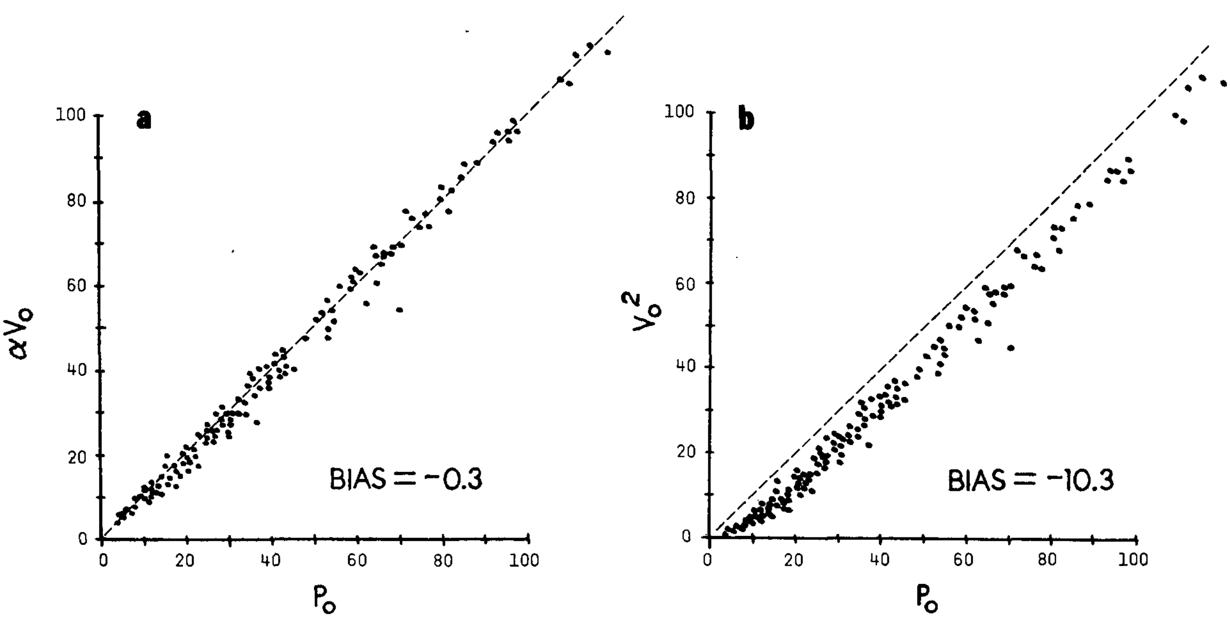


FIG. 9. A test of our empirically derived correction factor ($\alpha$) on an independent dataset (the COADS-update, 1980–1985) in the South China Sea: (a) pseudostress estimated as $\alpha \mathbf{V}_0$ (ordinate) versus true pseudostress, $\mathbf{P}_0$ (abcissa); (b) pseudostress estimated as $\mathbf{V}_0{}^2$ (ordinate) versus true pseudostress, $\mathbf{P}_0$ (abcissa). Indicated biases are average distance of points from 45° line. Units are m$^2$ s$^{-2}$.

## 7. Summary

Ship observations are inadequate over the tropical oceans for a useful analysis of the monthly mean wind and wind stress. Judicious use of auxilliary data meshed with available ship data, however, make possible a reasonable determination of the monthly mean wind. This paper takes the step of producing monthly mean pseudostress from the monthly mean wind by taking advantage of the fact that the tropical wind field has relatively low standard deviations which are essentially equal for both the meridional and zonal component of the wind and which change little from month to month. This simplifies the relationship between the square of the monthly mean wind ($\mathbf{V}_0{}^2$) and the monthly mean of the squares of each wind observation (the "true" pseudostress, $\mathbf{P}_0$). A single formula for a multiplying factor ($\alpha$), developed from year-round wind data, suffices to estimate the pseudostress from the monthly mean wind to within 10% of its true value for all tropical oceanic regions between 25°N to 25°S for all months. Tests using COADS and the COADS-update show that a good estimate of the monthly mean pseudostress can be computed from the monthly mean wind over the tropical oceans.

Estimation of the monthly averaged stress ($\tau_0$) from the monthly averaged pseudostress ($\mathbf{P}_0$) is dependent upon the choice of drag coefficient. A drag coefficient that increases with increasing wind speed causes the monthly averaged pseudostress to be an underestimate of the monthly averaged stress. The relative magnitude of this underestimate is greatest (10% or more) at low monthly averaged wind speeds (4 m $s^{-1}$ or less) and decreases with increasing wind speed.

*NOTE: Monthly wind stress data produced as described in this paper are available from the Department of Meteorology, University of Hawaii, for the tropical Pacific Ocean beginning December 1979.*

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