On Trends in Historical Marine Wind Data*

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ABSTRACT

Compilations of surface winds from ship reports since 1854 show a number of long period variations, including a trend toward strengthening winds over the past three decades. Some investigators indicate that these variations are real changes in the climate system, while others suggest that they are artifacts of the evolution of measurement techniques. In an attempt to resolve this issue, we have examined individual ship reports from three regions with high data densities: South China Sea, North Pacific, and North Atlantic shipping lanes.

We find that the apparent surface wind strengthening from the 1950s to the present is a consequence of the increasing use of anemometers in place of sea-state estimates. The specific causes are the operational use of an incorrect conversion from Beaufort force to wind speed, and the widespread assumption that the height of shipborne anemometers is 10 m, whereas the actual mean height is 19.3 m. Correcting the conversion scale and setting the height to be 20 m largely eliminates the trend. The adjustment of anemometer winds for stratification effects further increases the consistency between the measured and estimated winds. A formula for correcting the wind speeds available in standard averaged products is presented; in addition to wind speed, the ratio of estimated to measured observations and the average air-sea temperature difference are required.

Even with the correction, the pre-1950 winds appear to be weaker than the post-1950 winds. The most likely explanation is the absence of universal standards for sea state and Beaufort force before 1946. Possible remedies are discussed, but the task is daunting. Though this cautionary tale does not rule out the existence of real trends in surface winds, it does impugn their detectability.

1. Introduction

Scientific interest in historical surface wind data has increased substantially in recent years, mainly because of the importance of windstress forcing in the dynamics of the coupled tropical ocean and atmosphere. Surface wind stress is the essential driving for ocean models, and the needs of ocean models compel much of this interest.

The starting point for nearly all climatological marine wind data products is machine-readable files of historical surface weather reports from transient and weather ships maintained at major national meteorological centers. For example, the FSU (Florida State University) tropical Pacific Ocean monthly mean surface winds (Goldenberg and O'Brien 1981) for the years 1961–83 were derived by subjective analysis of ship reports in NOAA's National Climatic Data Center (NCDC) TDF-11 ship file. In the tropical Atlantic Ocean, a new surface wind and temperature database covering 1964–79 was developed from the same data source by Picaut et al. (1985) and updated to 1984 by Servain and Seva (1987). The most recent compilation, COADS (Comprehensive Ocean–Atmosphere Data Set; Woodruff et al. 1987), provides global monthly means of surface variables over the period 1854–1979, objectively calculated from over 70 million ship observations synthesized through computer-based quality checks and duplicate report elimination procedures from the over 100 million observations contained in a large number of machine-readable marine wind datasets.

Almost a decade ago, Busalacchi and O'Brien (1981) first demonstrated that available wind data for the tropical Pacific, poor as it was (and is), have enough information to allow a simple model to reproduce significant features of the El Niño signal. Progress since then has brought us to the threshold of operational ocean general circulation models for the tropical Pacific (Leetmaa 1987) and the tropical Atlantic (Merle and Morliere 1988). In addition, coupled models, generating initial conditions from wind data alone, have been

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used to predict El Niño (Cane et al. 1986; Barnett et al. 1988).

Climate problems typically call for the integration of ocean models over several decades or more. For example, establishing the skill of El Niño forecasting models requires retrospective forecasts over several events (viz Cane et al. 1986). Nevertheless, only a handful of ocean model simulations extending over more than a few years and driven by actual wind data has been reported. (For the Pacific: Latif 1987; Busalacchi and O'Brien 1981; Busalacchi et al. 1983; Seager 1989; Posmentier et al. 1989. For the Atlantic: Servain et al. 1985; Reverdin and Du Penhoat 1987). None venture into the data-poor years before 1947. Though not all call attention to it, all either remove the secular trend in the wind forcing or show trends in the simulated ocean variables that are not present in the observations. An explicit discussion of these trends is given in Posmentier et al. (1989). They conclude that, within the framework of widely accepted ocean physics, the strengthening of the Pacific trades indicated by the wind data is inconsistent with the absence of a similar trend in sea surface temperature and sea level. They therefore suggest that the trend in the winds is spurious. A similar conclusion was reached by Wright (1988).

Others suggest the trend is real. Whysall et al. (1987) assert that the FSU winds exhibit a strengthening of the zonal wind in the central and eastern tropical Pacific Ocean of about 1 m s^{-1} over the period 1961–83. Further, using a wind dataset compiled by the British Meteorological Office of monthly means in 5-degree squares over the period 1920–83, they find support for extending the trend back to the 1930s and argue for the existence of a major climatic anomaly in surface winds during roughly the years of World War II.

Ramage (1984) and Peterson and Hasse (1987) discuss the possible introduction of spurious very long-term trends into historical marine data by changes in the procedure used to derive wind speed equivalents of Beaufort force estimates. It appears from these studies that between the middle of the nineteenth and twentieth centuries, the major changes in Beaufort force estimation procedure (at first related to sail characteristics, and later, for steamships, to the appearance of the sea) and lack of standard Beaufort force sea state and Beaufort force wind speed equivalency relationships will probably forever prevent the separation of spurious trend from climatic change. In a further study, Ramage (1987) studied COADS monthly wind speed summaries in 2-degree latitude by 2-degree longitude boxes containing the major South China Sea trade route and found about a 1 m s^{-1} positive bias in wind speed averaged over 1950–79 relative to 1900–39. This difference was attributed mainly to two effects: 1) the 1946 formalization of the sea-state equivalents of Beaufort force; 2) beginning after 1950, the increasing number of marine wind observations based upon anemometer measurements.

The objective of the present study is to investigate whether, by working from individual ship reports rather than previously averaged summaries, it can be shown that trends arise from inhomogeneous wind observation methods, and to what extent any spurious trends found can be removed by adjusting the individual historical ship reports for such measurement biases.

This pilot study uses ship observations in three ocean regions characterized by relatively dense coverage of reports. The regions are the same South China Sea (SCS) trade route investigated by Ramage (1987) and segments of the most heavily traveled midlatitude trans-North Pacific and trans-North Atlantic shipping lanes. For several 2-degree squares in each area, we compute the march of mean seasonal wind speed anomalies since 1900 in three ways: first, directly from the individual wind speed observations as given in the TDF-11 data source; second, after the individual reports are adjusted to a common reference level of 20 meters, taking into account differences between measurement types; finally, after applying a stability correction. Trends are then calculated and compared within different historical periods beginning in 1950. Trends are not calculated through 1950 because the pre-1950 winds appear to be consistently weaker than the post-1950 winds. This is discussed further in section 6.

The analysis outlined above was carried out basically on two datasets. At first, we used all of the ship data in each region, after eliminating duplicate reports, taking the reported measured–estimated indicator code of the report at face value in the assignment of wind observation type. Second, we used a dataset for South China Sea only, eliminating ship reports in source decks in which the measured–estimated indicator code was apparently not correct. The analysis of all of the ship data in all three regions is described in section 4, while the analysis of the quality controlled dataset for the South China Sea is given in section 5. First, we describe our data source (section 2) and the wind speed adjustment procedures (section 3).

2. Data

All ship reports processed in this study are contained in the NOAA NCDC TDF-11 archives. Basically, the NCDC data are maintained in three separate files sorted by historical time periods: 1854–1969 (also referred to as "NCDC Atlas" file); 1970–79 (usually referred to as the "decade of the '70s" file); and the period 1980–present. Each of these large files consists of reports taken from a number of source "decks" (so-called because marine data were originally stored on computer cards before being transferred to tape). Figure 1 shows the locations of the 2-degree squares treated in each shipping lane and indicates the total number of ship reports in each square in the period 1900–84. For the second analysis referred to in the previous section, the South China Sea database was updated through 1987.

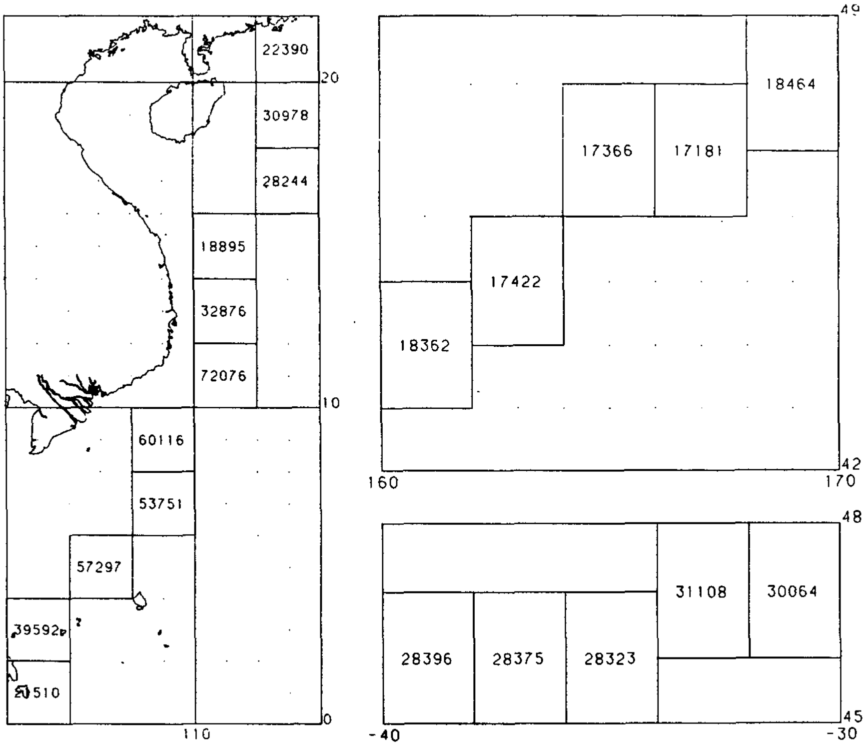

FIG. 1. Total number of ship reports (1900–84) in two-degree latitude–longitude squares studied: (a) South China Sea; (b) North Pacific Ocean; (c) North Atlantic Ocean.

Though attractive in many ways, we did not utilize the COADS source for this study. The COADS individual report files had not systematically retained from all source decks the character group containing the ship call sign, which might be needed to identify ship anemometer height. Apparently, the parts of the ship report including the wind group and the measured–estimated indicator were not subjected to the substantial quality control procedures applied to many other elements of the observation. Fortunately, the NCDC sources constitute by far the largest part of COADS. On a global basis, the NCDC "Atlas" and "decade of the '70s" files contain about 57 million reports compared to the final COADS tally of about 70 million reports. More specifically, in the SCS trade route, Ramage (1987) notes a total of 140 157 observations between 1900–39 and 344 964 observations between 1950–79 in COADS. After elimination of duplicate reports, following basically the procedures used in the development of COADS, our file contains 114 016 observations between 1900–39, and 252 851 observations between 1950–79. It is difficult to imagine how our results could be changed by the larger COADS dataset.

3. Calculation of wind speed

a. Adjustment of wind speed to 20-m reference level

The procedure used in this study to adjust ship wind speed reports to a standard level of 20 m has been used for nearly two decades in an analysis scheme used to specify synoptic marine surface wind fields for numerical ocean surface wave models (e.g., Cardone 1969; Cardone et al. 1982). In the procedure, all ship reports of surface wind speed are adjusted to the effective neutral stability 20-m equivalent wind speed. If the reported speed is based upon a Beaufort estimate, Cardone's (1969) Beaufort number–wind speed equivalency scale is used, and no further adjustment for stability is made. If the reported speed is measured, the speed is adjusted for anemometer heights different from 20 m and stability.

The effective neutral wind speed is defined as

$$U_e(Z) = (U_*/k)\log[Z/Z_0(U_*)] \qquad (1)$$

where U_* is friction velocity, k is the von Kármán constant, and Z_0 is a roughness parameter, generally a function of U_* in the marine surface layer. If the marine surface layer is neutrally stratified, the effective and actual 20-m mean wind speeds coincide. In a non-neutrally stratified surface layer, U_e is linked to the actual wind through U_*, which may be calculated from a single layer wind measurement and the air–sea temperature difference using stability-dependent profile forms and a roughness parameter form. (For a more detailed description of the algorithm used, see Cardone 1969; Ross et al. 1985.)

In fact, this is the way wind speed observations from ships based upon anemometer measurements are generally treated. That is, U_* is first calculated from the reported wind speed and air–sea temperature differences, then U_e is calculated from (1). Anemometer height is assigned, if possible, through a reference list of ship call sign versus anemometer height which contains about 3000 such heights, synthesized from various individual source lists, mainly WMO (1976). Still, for a large number of observations in which the ship code wind indicator indicates that wind speed was indeed measured, either the call sign or height is missing. For such cases, the adjustment algorithm assigns a height of 20 m, which is close to the average of all known heights. Table 1 gives the distribution of ship anemometer heights in the list as a function of the leading character in the call sign. The average height overall is 19.3 m, while the average height for most call sign groups (call sign is related roughly to country of registry, e.g., J—Japan, U—USSR) ranges between 15 and 25 m. The call sign group beginning with "4" has the lowest average height, because this group consists mainly of NOAA NDBO moored buoys, whose anemometers are maintained at 5 or 10 m, depending on hull type and payload. Anemometer heights on modern fleets of container vessels vary upwards of 25–30 m, while heights on exploratory drillships and semi-submersibles range between 40 and 80 m. There are few, if any, reports from buoys, drillships or semisubmersible platforms in the regions studied.

TABLE 1. Anemometer heights on marine platforms (vessels, buoys, rigs) sorted by leading character on call sign (1st). Table gives number of heights on file, average height, standard deviation, minimum and maximum height within group. The mean height of the 2964 entries is 19.3 m.

1st	Number of heights	Average height (m)	Std dev (m)	Min (m)	Max (m)
0	0				
1	0				
2	0				
3	30	23.2	9.4	5	41
4	50	9.3	4.3	5	23
5	44	26.7	9.2	5	42
6	63	21.5	10.3	3	43
7	0				
8	1	28.0	0.0	28	28
9	17	23.6	3.1	18	29
A	30	27.6	6.7	9	38
B	8	24.6	2.8	21	28
C	40	20.7	6.4	10	30
D	26	23.4	3.0	14	28
E	119	17.8	7.9	3	41
F	191	20.7	6.9	7	52
G	9	23.3	11.0	12	50
H	29	24.7	9.2	6	45
I	18	21.7	4.7	12	28
J	530	29.6	7.2	8	50
K	33	34.4	20.9	13	80
L	18	30.1	13.0	20	80
M	0				
N	77	20.1	5.7	8	42
O	3	38.7	2.3	36	40
P	2	22.0	9.9	15	29
Q	0				
R	0				
S	223	13.8	3.6	5	26
T	4	15.0	4.2	11	21
U	1133	13.8	3.6	3	31
V	58	26.7	17.2	6	80
W	162	20.1	9.4	8	80
X	0				
Y	0				
Z	46	12.5	4.7	6	26

As part of the present study, a sensitivity analysis was carried out in which the actual heights were assigned to measured winds whenever an anemometer height could be found to match the report call sign, and the wind corrected to 20 m, all unknown heights being assigned to 20 m. The results are virtually the same as the analysis, whose results are given in this paper, in which the heights of all measured winds were assigned to 20 m. We attribute this mainly to the small proportion of the total population of measured winds for which an assignment of anemometer height is possible. For example, for the total South China Sea ship report database, of the 84 171 measured ship reports in the past 40 years, only 6815 call sign–height matches were found. Thus, the direct calculation did not yield a conclusive result on the effect of varying anemometer height. Because a misassignment of ±5 m typically results in an error of less than 5%, we expect the effect of randomly distributed heights on climatologies to be negligible. However, the use of a mean of 20 m instead of 10 m, which has traditionally been assigned to marine surface winds, corrects an error that is significant because it systematically biases anemometer winds high.

b. *Beaufort force wind speed equivalency scale*

Reconciliation of measured wind speeds over open sea with wind speed equivalents of Beaufort force has been a subject of continuing interest to the Commission for Marine Meteorology (CMM) of the WMO. The first standard Beaufort force wind-speed equivalency scale was introduced in 1946, based upon data first published in 1906. A number of revisions have been proposed (Verploegh 1956; Cardone 1969; Kaufeld 1981), and in 1970 the WMO introduced a revised scale (WMO 1970) of wind speed equivalents for use in scientific studies, though the operational scale (in use since 1946) was not altered. The issue remains of critical importance, since even today approximately 50% of wind observations received from merchant ships in the North Atlantic and about 20% of wind observations in the North Pacific are derived from Beaufort estimates.

Figure 2 compares several of the various scales referred to above. The official scale is purported to relate to 10-m level wind speeds. Cardone (1969) reviewed and synthesized series of simultaneous observations

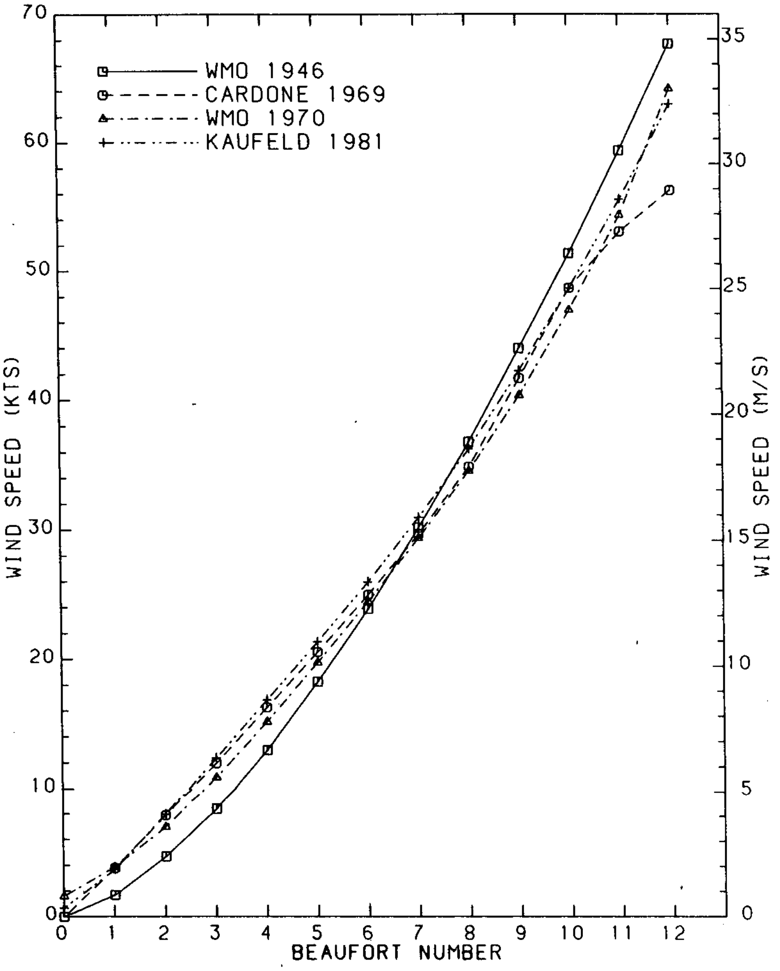

FIG. 2. Comparison of Beaufort number–wind speed equivalents.

from British and Canadian weather ships, in which one observer read the anemometer dial and another observer, separated from the first, estimated the Beaufort force. Cardone's scale relates the Beaufort number to the 20-m level (the average anemometer height on the ships involved). Kaufeld (1981) compared Beaufort-based wind speed observations from transient ships and wind measurements from six North Atlantic Ocean weather ships for neighboring and simultaneous observation pairs. His scale was supported both from comparison of cumulative frequency distributions of wind speed and from direct correlation of observation pairs. Kaufeld's scale presumably relates to the wind speed at 25-m, the average anemometer height of the ensemble of weather ships used in his analysis. The wind speed reference level for the WMO scientific scale is not specified.

While the newer scales shown in Fig. 2 differ slightly from each other, they are all consistent with the idea that the operational (1946) scale understates light winds and overstates strong winds. Some of the small differences between Kaufeld's scale and Cardone's scale at higher winds (Beaufort 6 to 11) may be due to anemometer height differences between the two underlying datasets. For a logarithmic profile, using a roughness law consistent with the drag law of Large and Pond (1981), the over-water wind speed at 25 m at neutral stability is about 3% greater than the wind speed at 20 m, while the wind speed at 20 m is about 8% greater than the wind speed at 10 m. However, the differences between the operational scale and the newer calibrated scales cannot be explained in terms of reference level differences alone. The difference between Kaufeld's scale and Cardone's scale at Beaufort force 12 probably arises from the very limited data there. The dataset analyzed by Cardone, for example, had only nine occurrences of Beaufort force 12 out of 5,499 data pairs.

Wind speed reports based upon Beaufort force estimates are "corrected" in this study to 20 m, with a double conversion. The reported wind speed, derived presumably from the operational scale, is taken back to Beaufort force number. This force estimate is then converted to an equivalent 20-m wind speed using Cardone's scale. No further correction for stratification is made on the assumption that Beaufort estimates already incorporate this effect. This is because the visual estimate is dominated by the appearance of the sea surface, which is more a result of surface stress than 20 m wind. The conversions, made from tables in practice, are well approximated by (Cardone 1969):

$$U_{20} = 2.16 U_r^{7/9},$$

where U_r is the reported (Beaufort) wind speed in knots.

4. Trend analysis in three regions on the full dataset

The results presented in this section are taken from our analysis of the full TDF-11 ship report archive assembled for this study. In this first analysis, all measured winds were assigned an anemometer height of 20 m, and stratification was assumed neutral throughout. Stability effects are considered in the analysis presented in section 5. The measured–estimated indicator code was taken to classify winds as either anemometer-based or Beaufort estimates.

In each region, the files of individual ship reports were reduced to two time series of monthly wind speed anomalies. That is, one of the series which we shall refer to as "reported" was developed from the archived wind speeds, the second referred to as "adjusted" was produced from reports adjusted to 20-meter wind speeds. However, since in this first analysis, anemometer height is assumed 20 m throughout and stability is not considered, the "adjusted" series consists of measured winds as reported and estimated winds adjusted to 20 m using Cardone's scale. The two time series were calculated for each 2-degree square within a shipping lane as well as for the shipping lane as a whole. The individual monthly mean wind speed anomalies for both reported and adjusted series were calculated using 20-year (1965–84) normals derived from adjusted wind speeds. The time series of individual monthly mean anomalies were smoothed to seasonal mean anomalies, with the winter season defined as the months December, January, February, and so forth.

The time series are described below for each region, at first qualitatively, over the entire period 1900–84. For the period 1950–84, linear regression of seasonal wind speed anomaly on time was carried out on both reported and adjusted series. The slopes are compared for this entire period as well as for shorter periods within this span.

a. South China Sea

The surface wind climate along this entire trade route is dominated by the Asian monsoon, with steady northeasterlies in winter, southwesterlies in summer, and transition seasons in between. Mean speeds range from less than 5 m s^{-1} near the equator in spring and fall to greater than 10 m s^{-1} in winter in most squares north of 10°N.

Figure 3 compares the reported and adjusted series over the entire period. The main properties of the reported South China Sea series are very similar to the

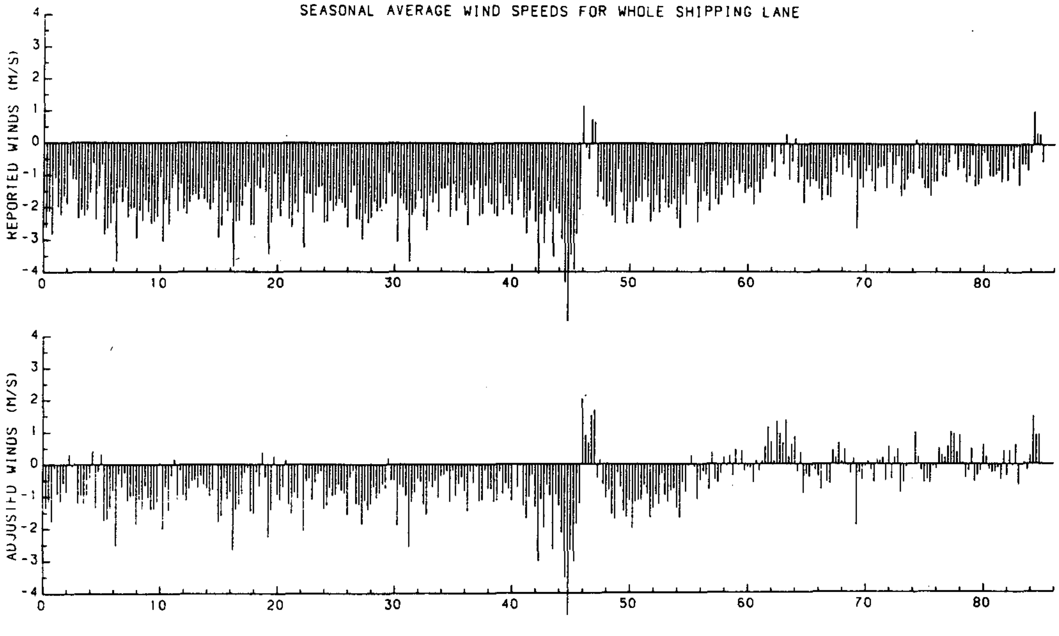

FIG. 3. Reported (upper) and adjusted (lower) seasonal average wind speed anomaly (1900–84) in South China Sea shipping lane, relative to 20-year (1965–84) averages of adjusted ship winds.

20th century portion of the comparable global series developed from COADS "trimmed" data by Ramage (1987). Wind speeds in the first four decades of this century are systematically lower than in the most recent three decades. Also, from about 1950 forward, the period of most interest to modelers, there is an apparent trend in wind speed anomaly. Between these two broad periods, roughly coinciding with the end of World War II, there is an apparent large anomaly oscillation.

The first reports indicated to be measured winds do not appear in this region until June 1947. All earlier reports are presumably Beaufort estimates, yet the adjustment of Beaufort winds leaves an average negative wind speed anomaly for the pre-1950 period relative to the 1965–84 adjusted normals. As discussed also by Ramage (1987), this anomaly persistence is probably related to the absence of a standard Beaufort-force sea-state equivalence scale until 1946.

Inhomogeneity in source deck may also introduce errors to the time series. Figure 4 shows the contributions of each source deck in this trade route over 1940–84. The apparent large anomaly oscillation between 1944 and 1947 appears especially suspect, since almost all ship reports in these years come from two decks containing a small number of U.S. Navy observations. There is also a relative deficit of observations between 1962 and 1964 when the gap between deck 119 and 128 in this period leaves only deck 116.

Figure 5a shows the partition found between Beaufort estimates and measured wind speeds between 1950–84 in the shipping lane as a whole. These distributions only approximate the true mix. For example, all measured reports between 1947–55 are contributed by deck 189 (Netherlands Marine Observations), within which all reports are coded as measured. Also, between 1956–63 all wind reports are coded as estimated on the relevant source decks though almost certainly some measured winds must be present. To determine accurate distributions, if at all possible, would require tedious investigations of the history for each source deck of the precise observation encoding, punching, data handling, and archive procedures, most of which are not presently documented. In the next section we present results of our partially successful attempts to identify and filter from the data base, source decks with unreliable measured–estimated indicators. The analysis of the total data base, however, does not contradict the results obtained from the data base subjected to tighter, albeit tedious, quality control.

The alternate time histories of seasonal wind speed anomaly for the shipping lane as a whole are shown in Fig. 6. Superimposed on each figure are the trend lines derived from linear regression for the indicated historical periods, each ending in 1984. The slopes of the trend lines are tabulated over all squares and periods in Table 2.

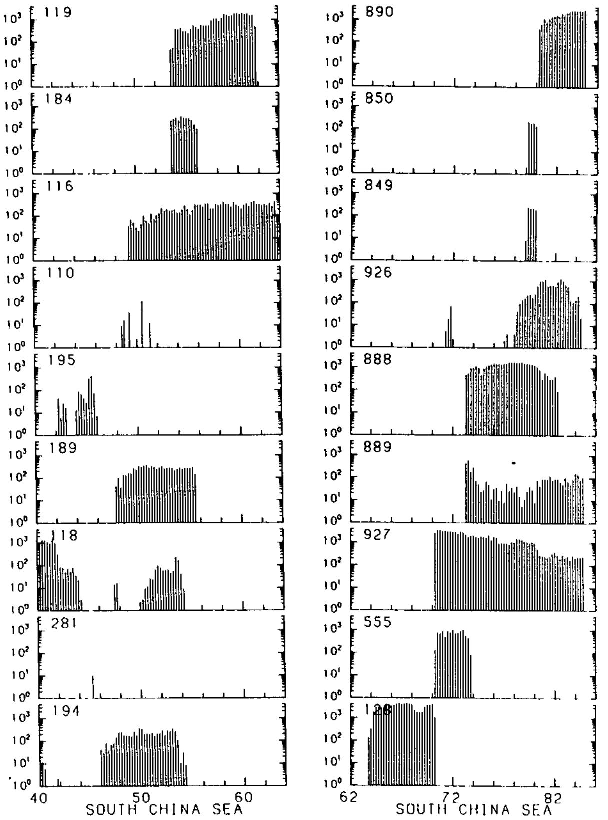

FIG. 4. Total number of ship reports per season (1940–84) and source deck in South China Sea shipping lane. The following listing is the key to the source deck number: 119 Japanese Ship Observations No. 2, 184 Great Britain Marine Observations, 116 U.S. Merchant Marine, 110 U.S. Navy Marine Observations, 195 U.S. Navy Ship Logs, 189 Netherlands Marine Observations, 118 Japanese Ship Observations No. 1, 194 Great Britain Marine Observations, 890 National Meteorological Center Global Telecommunications (GTS), 850 German First GARP Global Experiment (FGGE), 849 FGGE, 926 WMO Foreign Exchange Data, 888 Global Weather Center (GTS), 889 AUTODIN (U.S. Navy) GTS, 927 U.S. Merchant and Navy Manuscript Observations, 555 Fleet Numerical Oceanography Center (Monterey) GTS, 128 International Marine Observations.

Especially for periods beginning in 1955 and 1960, there is a significant reduction in slope (by factors of 3 to 6) in the adjusted series. The positive trend in both reported and adjusted trend lines for the 1950–84 period arises mainly because of the temporally coherent negative anomalies in both series in the early 1950s. This anomaly appears in all subsquares and may be coming from the same effect seen in reported or adjusted Beaufort estimates between 1900 and 1940. Possibly, this represents a period during which the 1946 standard for Beaufort force sea-state equivalents became gradually accepted in practice.

Table 2 (and plots such as Fig. 6 for individual subsquares, not shown) shows that the reduction in trend overall arises mainly in the near-equatorial subsquares. The adjustment procedure has virtually no effect at 20°N. Here, a much higher proportion of Beaufort force reports are in the range 4–8, for which the WMO 1946 and Cardone 1969 scales of wind speed equiva-

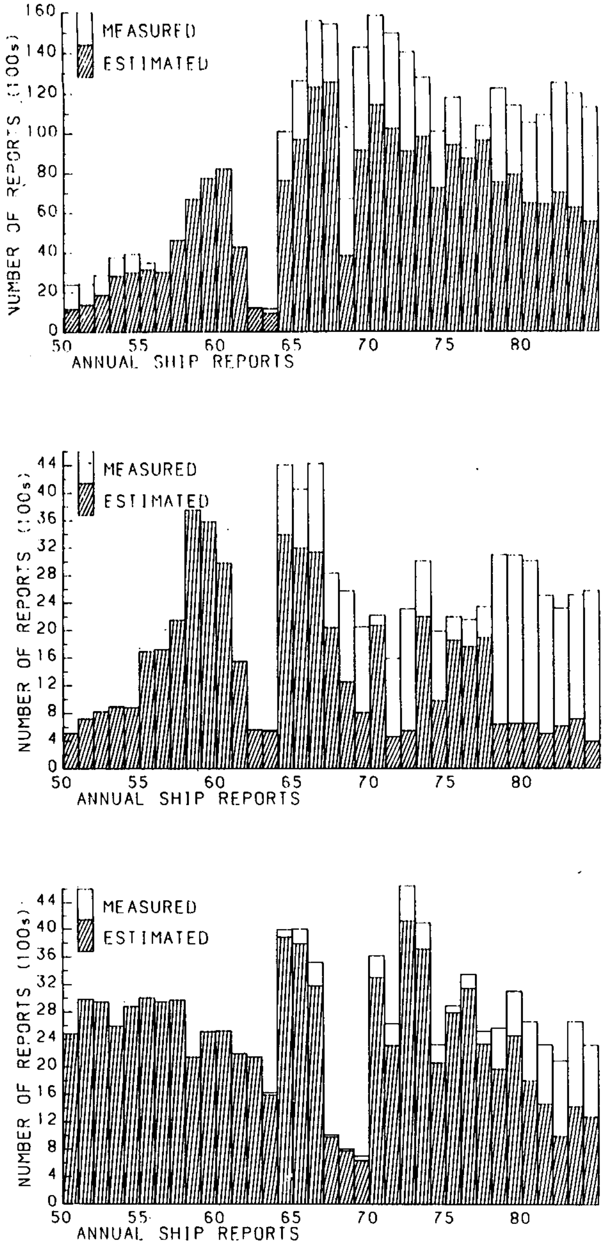

FIG. 5. Annual number of ship reports (1950–84) sorted by reported measured–estimated wind indicator, in shipping lanes studied of South China Sea (upper), North Pacific (middle), North Atlantic Ocean (lower).

lents agree. Given the high steadiness of the winds along this trade route, the seasonal mean anomalies will therefore show little response to the adjustment procedure where the climatology places the mean wind in the vicinity of these Beaufort forces. There remains the possibility then of a secular change in wind in subtropical parts of the South China Sea.

b. North Pacific Ocean

The mix of source decks which contribute ship reports in this region is much like that of the South China Sea region, except that deck 189 (Netherlands) does not contribute. As a result, there are no apparent measured winds before 1963, after which inclusion of a measured–estimated indicator on GTS reports was standardized (Fig. 5b). Over the whole period 1900–84 the adjusted series remain on average negatively biased before about 1940. The large anomaly oscillation between 1944 and 1947 is not so evident here because the contributing U.S. Navy source decks are so devoid of observations that for several seasons in the period no reports were found in this region.

Because the wind speed climate did not vary spatially in 1950–84 over this midlatitude region, we show the results of the trend analysis in Fig. 7 only for the average of all selected subsquares which constitute this shipping lane. The adjusted series exhibit much lower trends; the slope is reduced by about a factor of 4 for all periods beginning in 1965 and earlier. Note the large increase in the proportion of measured winds in this region in the past few decades, shown in Fig. 5b.

c. North Atlantic Ocean

The main difference between the source decks which apply to this region and the other two regions studied is the relatively small contribution of Japanese decks

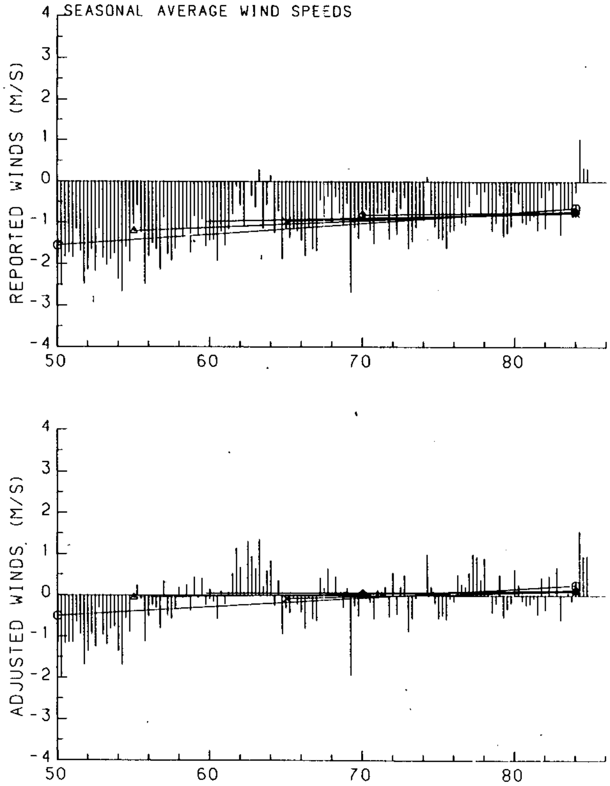

FIG. 6. Seasonal wind speed anomaly (1950–84) of reported and adjusted ship reports in South China Sea shipping lane. Anomaly is relative to 20-year averages (1965–84) of adjusted wind speeds. Trend lines shown are derived from linear regression of anomaly on year in indicated periods.

TABLE 2. Slope (m s^{-1}/yr) in linear regression of seasonal wind speed anomaly on year for 2-degree subsquares and all squares together of South China Sea shipping lane, over indicated time periods. Within each period, upper slope is based on reported winds, lower slope is based on adjusted winds (see Fig. 1, subsquares are numbered from south to north).

	South China Sea subsquare											
Period	1	2	3	4	5	6	7	8	9	10	11	All
1950–84	.021	.024	.023	.029	.029	.032	.022	.025	.016	.022	.040	.027
	.012	.021	.018	.021	.023	.023	.022	.028	.020	.027	.040	.022
1955–84	.011	.016	.013	.018	.019	.021	.012	.016	.007	.017	.031	.016
	−.002	.006	.002	.004	.007	.009	.005	.010	.004	.014	.023	.005
1960–84	.013	.013	.008	.012	.009	.023	.007	.005	.002	.009	.028	.009
	.002	.005	−.001	.002	.001	.005	.002	.003	.000	.009	.022	.002
1965–84	.011	.014	.011	.011	.017	.015	.010	.001	−.001	.009	.002	.010
	.007	.011	.008	.008	.010	.013	.008	.001	−.001	.010	.002	.010
1970–84	.004	.007	.005	.006	.010	.011	.005	−.008	−.009	−.000	.013	.005
	.004	.006	.005	.005	.009	.011	.004	−.002	−.007	.008	.013	.005

in the North Atlantic, though, of course, the several source decks derived from GTS collections include a varied mix of sources within themselves. The alternate time series for the whole period 1900–84 resemble the series derived in the other two regions before 1940 as regards the negative bias. There is evidence from analysis of pressure data that the North Atlantic westerlies were stronger in the early 20th century than after World War II (Parker and Folland 1988), further supporting our suspicion that the pre-1950 wind speed deficit is spurious. However, after 1950, as shown in Fig. 8, there is relatively little trend in either the reported or measured series. There is a suggestion of a slight negative trend in all periods beginning after 1955. Figure 5c shows the distribution of measured and estimated wind speeds in this region. The tendency for increased incidence of measured winds in this region is much less pronounced than in the Pacific regions.

5. Further adjustments: the quality controlled dataset

The analysis of the full dataset suggested that the measured–estimated indicator was, at least in some

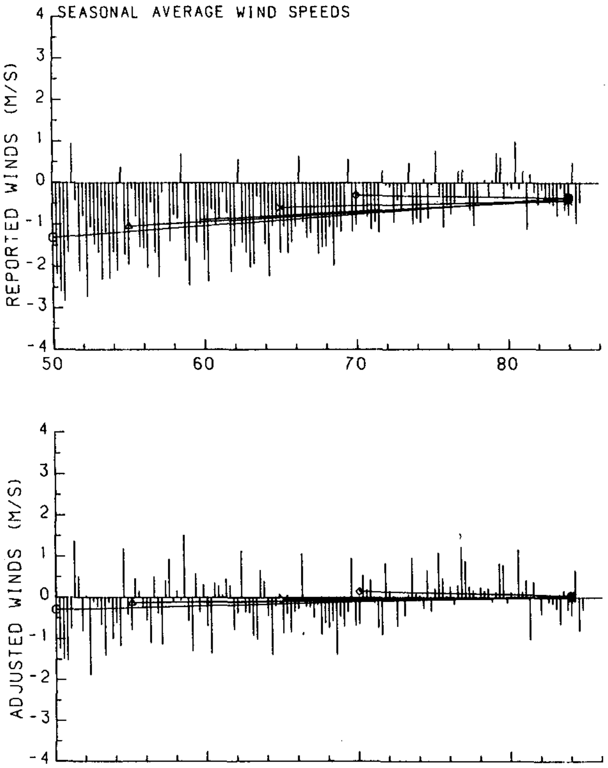

FIG. 7. As in Fig. 6, except for North Pacific Ocean.

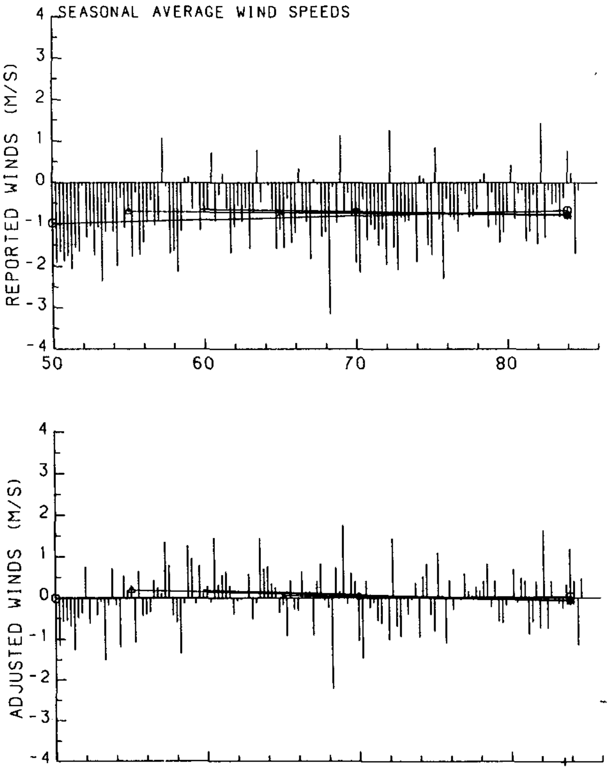

FIG. 8. As in Fig. 6, except for North Atlantic Ocean.

source decks, not a reliable measure of the wind measurement type. A few examples were noted above. This problem was confirmed when reports from vessels known to carry anemometers were tracked through time and, in many cases, through different source decks. It seems that erroneous measured–estimated codes characterized certain decks and even certain time periods within individual decks. This is perhaps explainable in that some source decks are in fact collections of several heterogeneous sources. Another possible source of error may be related to the way the indicator is coded: "blank" for estimated, "zero" for measured, with no allowance for a "missing" indicator.

A relatively simple scheme was devised that effectively filters erroneously coded reports. The filtering was applied only to the South China Sea data, since it reduces the amount of data significantly. Even there, several gaps were in the resultant dataset; that is, there were several seasons within the past two decades left with no reports. The total number of ship reports in the whole shipping lane in the 20-year base period 1965–84 was reduced from 264 806 to 157 358.

The procedure requires sorting and tallying the ship reports in the shipping lane by year and month and indicated measurement type. Between January 1900 and May 1947 all reports were treated to be estimated. Between June 1947 and May 1955 all reports were indicated to be estimated, except for reports in deck 189 which were all indicated to be measured, probably erroneously. Reliably coded indicators of measured winds first appear in April 1964, in deck 128. Between 1964 and 1984, it was relatively easy to identify specific time periods within specific decks in which the ratio of measured to estimated winds behaved erratically from month to month or fell outside of reasonable ranges established by most other decks. These periods were excluded. Table 3 shows the admitted decks and time periods. Outside the indicated time periods, the ratio often discontinuously passed into near 0 or 1 within specific decks.

The trend analysis was repeated on the filtered dataset. In addition, the measured winds were further adjusted for stratification in the calculation of means, anomalies and trends for the adjusted series. As noted in section 3, the calculation of the effective-neutral 20-m wind from measured winds requires knowledge of anemometer height and air–sea temperature difference (or more precisely, the air–sea virtual potential tem-

TABLE 3. Time periods and source decks admitted into filtered ship report database, based upon reliability of measured–estimated indicator. Entry identifies year/month limits of admitted data.

Year (1900s)	Source deck								
	116	128	555	849	850	888	890	926	927
56	5601								
57	1								
58	1								
59	1								
60	1								
61	1								
62	1								
63	6306								
64		6404							
65		1							
66		1							
67		1							
68		1							
69		6912							
70			7012						7001
71			1					7101	1
72			1					(7107)	1
73			7307						1
74						7405			1
75						(7412)			1
76									7601
77									7712
78				7812	7812	7801			1
79				7911	7911	1			1
80						8005	8001		1
81							1		1
82							1		1
83							1		1
84							1		1
85							1		1
86							8612		1
87									8712

perature difference). As in the earlier analysis, too few height matches were found to make the height assignment effective and 20 m was assumed throughout, though there appears to be little error introduced by assignment of a mean height of 20 m to all anemometer based reports.

To provide air–sea temperature differences for the adjustment of measured reports, we calculated a mean air–sea temperature for each month and each subsquare in the shipping lane by averaging the reports in the relatively data-rich "decade of the 70s" file of filtered data. This was done because air or sea temperature is often missing in individual reports, which otherwise contain valid wind data. The monthly mean climatological difference, which ranges from +0.2°C to −1.3°C, is almost always negative, indicating unstable stratification. After correction for moisture stratification (a relative humidity of 75% was assumed throughout), the virtual potential temperature difference is offset from the air–sea temperature difference by about −1°C, and even the areas and months with slightly positive air–sea temperature difference become unstably stratified.

As a check on the consistency of the adjustments of estimated and measured wind speeds, we compared monthly means computed separately for each type, in each subsquare, and each month between 1965 and 1984. The means were computed only if there were at least 15 ship observations of each type in a given square in a month/year. This condition was satisfied in 1066 of the possible 2640 monthly means (11 subsquares × 20 years × 12 months). In each case, the measured mean (with or without stability correction) is plotted along the abscissa, and the estimated mean (with or without the scale adjustment) along the ordinate. In all four cases the scatter about a best fit line is about the same, corresponding to a standard deviation of approximately 0.8 m s^{-1}. However, the departure from the 45 degree line, the locus of consistent observations, differs among the four. In Fig. 9a, each axis is just as reported, so that here the two types are compared in the form in standard use. As expected for this range of wind speeds on the basis of the earlier cited studies of the Beaufort scale wind equivalents, the estimated winds are systematically lower than the measured winds: 83% of the points fall below the 45 degree line while the mean difference is 0.75 m s^{-1}.

Adjustment of estimated winds only, Fig. 9b, brings the means between the two data types into somewhat closer agreement: the mean difference is reduced to 0.53 m s^{-1} and the ratio of points below the line is 0.24. However, agreement is still far from satisfactory. A more thorough look at the plot reveals that the two types are now consistent at higher wind speeds (say 9–14 m s^{-1}), but the estimated winds are systematically higher at low winds speeds. The light winds in the South China Seas would tend to occur in unstable conditions, when treating a 20-m measured wind as if the atmosphere were neutrally stratified would understate the surface stress. We further reason that the Beaufort estimate, being based on the appearance of the sea, is more a measure of wind stress at the surface than of wind speed at any particular level. Hence there is reason to believe that adjusting for stability will further reduce the discrepancy.

Note from Fig. 9c that the stability correction alone, without the equivalency scale adjustment, only makes matters worse. Figure 9d shows the desired result: adjustment of estimated winds for Beaufort scale effects and measured winds for stratification provides the greatest consistency between the monthly means. The mean difference is only 0.15 m s^{-1} and the ratio is 0.42, close to the ideal one-half.

The results of the comparative trend analysis on the filtered dataset, in which both estimates and measurements are adjusted in the "adjusted" series, are shown in Fig. 10 (the whole shipping lane). The series shown runs from 1955 to 1987, as opposed to the series in Fig. 6 based upon the total data set, which covers 1950–84. The base period used for the calculation of anomalies remains 1965–84, and again the base was computed from the adjusted wind speeds. Trend lines are computed for two periods: 1956–87, and 1965–84. Again, we find that over the past 30 years or so, the trend toward strengthening winds, shown in the reported series, is reduced by an order of magnitude (in slope) in the adjusted series, for the series as a whole, and for lower latitude (0°–10°N) subsquares in particular (not shown). Over the 20-year period 1965–84, the reduction in trend is not nearly so large.

6. Discussion

There are a number of trends and interannual oscillations in the climate record that most likely reflect real variations in the earth's climate. Presumably at least some of these are accompanied by changes in the surface wind field over the oceans. In view of the high probability that the ocean participates actively in any low-frequency variations in the climate system and the certainty that the surface winds drive the ocean circulation, surface mixing, and heat exchange, a knowledge of these wind changes is clearly desirable.

Our investigation reinforces the pessimism of earlier studies (Ramage 1987; Peterson and Hasse 1987) for the years before 1950. The lack of standardization of either sea-state description or Beaufort scale means that, in its commonly available form, the variations in the wind data are likely to be due to variations in reporting procedures. This is not to say that there were no significant real changes in the winds, but it does say that their detection will be difficult. A study of each country's procedures (e.g., as documented in their mariner's manuals) would seem to be needed to assign a consistent wind speed to each reported Beaufort number. Information about each ship, such as the call sign giving country of origin, must also be available. The apparently consistent bias of the 1900–50 data

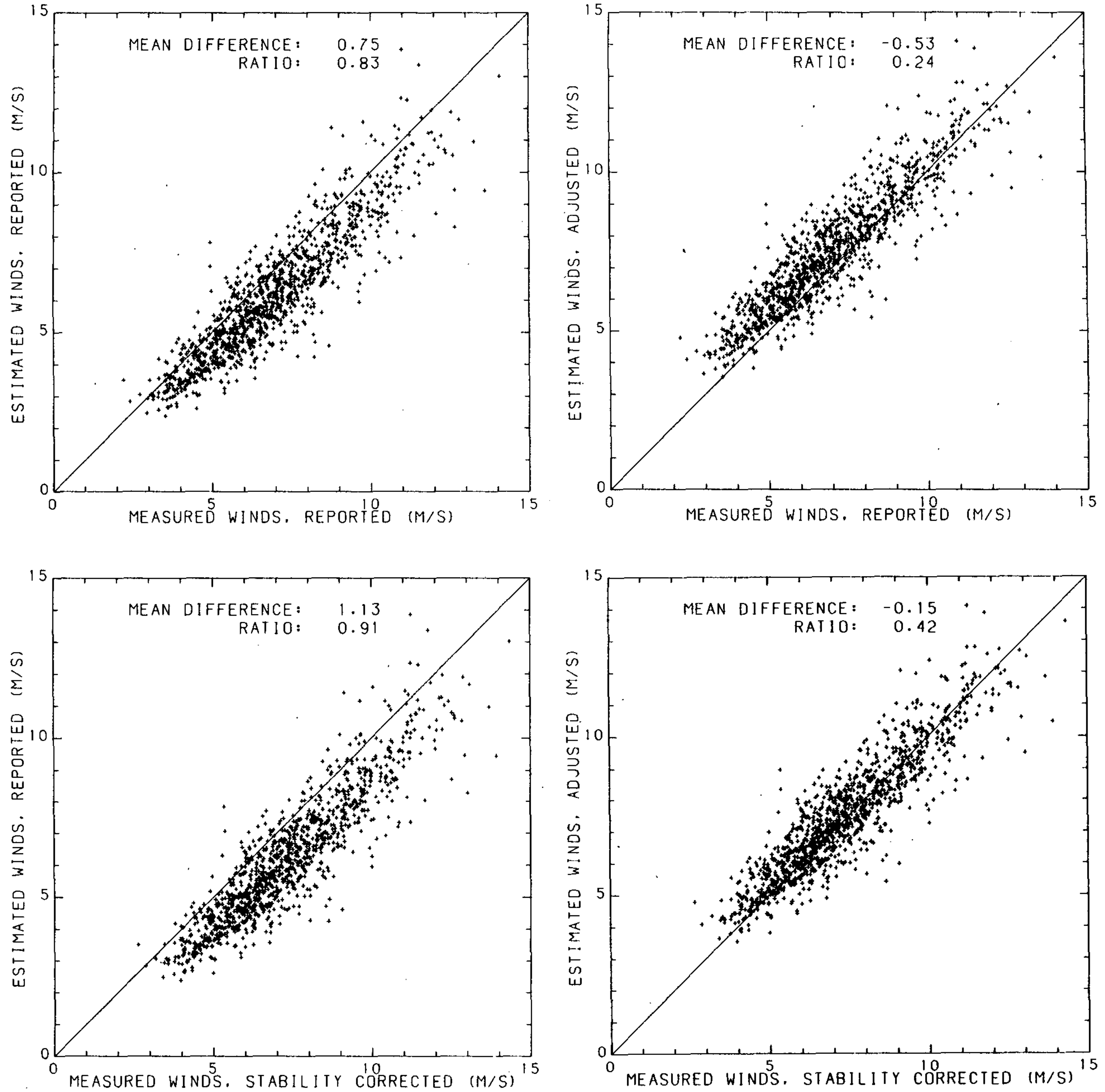

FIG. 9. Comparison of monthly mean wind speed in two-degree latitude–longitude squares of the South China Sea shipping lane (1965–84) from (a) estimated and measured ship winds as reported, (b) adjusted estimated winds and reported measured winds, (c) reported estimated winds and adjusted measured winds, (d) both estimated and measured winds adjusted. The mean difference and the ratio of points below the line to total points are given as well.

(viz. Fig. 3) holds out some hope that the above is overly pessimistic, but those asserting that a trustworthy climate signal can be extracted from the pre-1950 wind data have the burden of proof. We anticipate that a successful strategy will have to make use of data auxiliary to wind observations, such as surface pressure (cf. Wright 1988).

The data from the early 1950s is problematic; our best guess is that it is a transition period in which the international standard promulgated in 1946 gradually gained adherents. Thereafter the principal problem with wind datasets is solvable: the widely used 1946 WMO Beaufort force wind speed equivalency scale is in error. This problem was identified twenty years ago (Cardone 1969; WMO 1970) and is common knowledge in the wave modeling community. Corrected formulas are shown in Fig. 2. A comparison of Fig. 9a and 9b or the two panels of Fig. 10 illustrates the effect

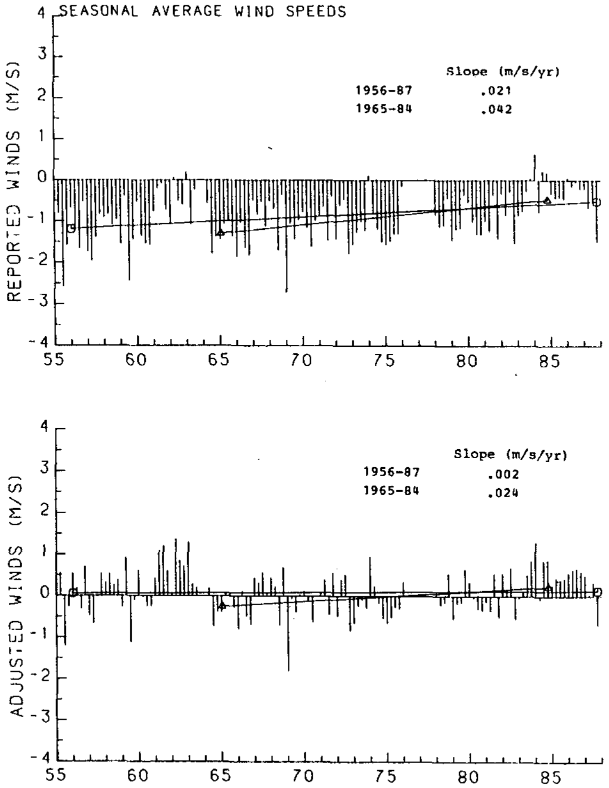

FIG. 10. As in Fig. 6, except for quality-controlled data set in period 1955–87, and both estimated and measured winds corrected in the adjusted series.

of this error, while a comparison of Fig. 9d with 9b shows the importance of accounting for stability at low wind speed.

It would be advantageous to correct marine surface wind data products such as the COADS monthly averages or the FSU wind field analyses without having to reconstruct them from scratch. Figure 11 is an attempt to meet this need: given the average wind speed as reported ship winds—which is the speed given in most climate data products—and the percentage of ship reports of estimated winds using presumably the 1946 Beaufort force-wind speed equivalency, and the air-sea temperature difference, applied to correction of all measured winds (assumed at 20-m height), we have calculated the adjusted wind using the Cardone (1969) equivalency scale and surface layer wind profile model. The difference between the adjusted and reported average wind speed is shown in Fig. 11 for various percentages of data obtained from Beaufort estimates and three stability categories. Unfortunately, the percentage of estimated winds has considerable spatial and temporal variation. Moreover, it is often reported incorrectly.

The data for stability are another source of difficulty. Humidity and air-sea temperature differences are not always reported and are often unreliable. For example, it is the well-founded practice of the British Meteorological Office to disregard all daytime air temperature measurements. Careful treatment and the ability to do some averaging can reduce the problem. Fortunately, stability has the largest relative effect on light winds and unstable conditions, and because a large relative error in a light wind is still a small absolute error, the effect on the ocean is usually small. The principal exception is the equatorial ocean, which is so well tuned to the wind that even small absolute wind errors are non-negligible. A correction based upon a mean air–sea temperature difference should work reasonably well in the tropics, where this field exhibits relatively high spatial and temporal coherence.

In contrast, over the middle and high latitude oceans, stability variations, including changes of sign, typically occur on synoptic time and space scales. For monthly mean or more highly averaged wind products, the net effect of such stability variations on the higher winds prevailing there is likely to be negligible. For wind products with higher temporal resolution it may be necessary to go back to the individual observations and compute the adjusted mean winds directly.

Even with the adjustment procedures described, numerous problems remain which limit the quality of the data. The Beaufort estimate has limited precision and is only as good as the observer. The corrected scale was constructed from a limited data base: the differences of the three "corrected" scales in Fig. 2 are a measure of this uncertainty. We have taken the Beaufort force wind equivalent as a direct estimate of the effective neutral wind, since this is the wind which relates to the near-surface wind profile in an arbitrary stratification and which therefore affects the appearance of the sea. Any attempts by the observer to modify his Beaufort estimate based upon the "feel of the wind in the face" would tend to violate that assumption.

Anemometer-based winds are subject to a number of error sources not accounted for here, such as poor instrument calibration, flow distortion effects, improper averaging intervals, and incorrect conversion from "apparent wind" to true wind (e.g., see Dobson 1981). The true height of a measured wind is rarely known, though with our reasonable default (20 m rather than 10 m) the error this causes is typically less than 5% and is unbiased. Uncertainties in height may be compounded by uncertainties in the stability.

All of the difficulties mentioned in the previous paragraphs would seem to introduce *random* errors, which can be expected to average out if the data are not too sparse. The incorrect equivalency scale is more pernicious because it creates *systematic* errors. Because it is biased low at low wind speed and high at high wind speed, it alters patterns as well as overall amplitudes. For example, the wind stress curl will be altered more than the wind stress itself. Our results strongly support Ramage's (1987) contention that the strengthening of the trades from the 1950s onward is

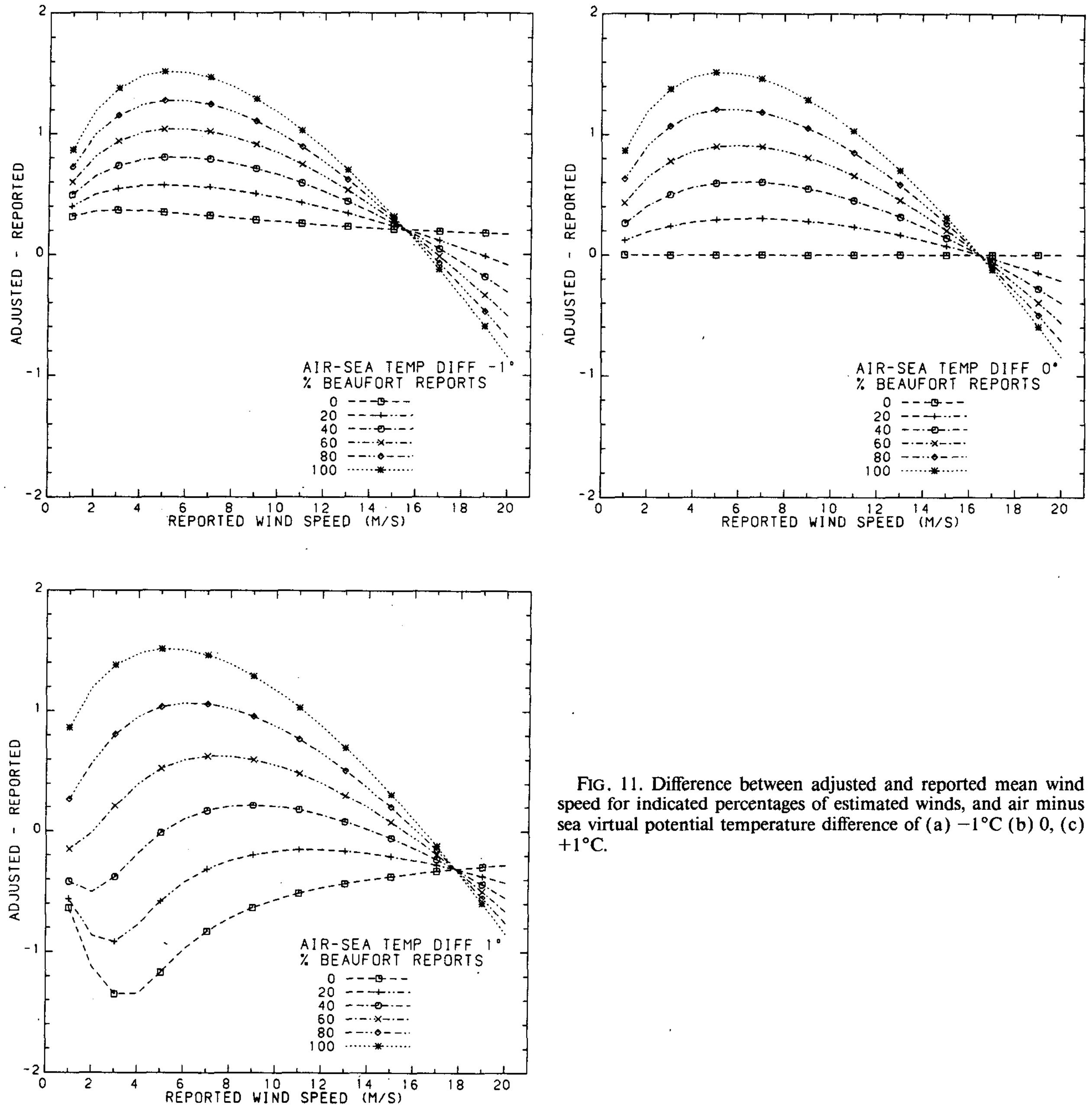

FIG. 11. Difference between adjusted and reported mean wind speed for indicated percentages of estimated winds, and air minus sea virtual potential temperature difference of (a) −1°C (b) 0, (c) +1°C.

a consequence of the change to measured winds rather than the climate change suggested by Whysall et al. (1987). Furthermore, the elimination of this trend in the winds eliminates the apparent inconsistency between wind and ocean data pointed out by Posmentier et al. (1989). A recalculation of the wind fields with the corrected equivalency scale should be decisive.

The corrected scale reduced but did not eliminate the low bias of pre-World War II winds relative to the post-war data. (The striking mid-1940s anomalies are almost certainly due to exclusive reliance on the U.S. Navy source deck for this period). Though we have not proven it, our experience with the post-1950s data leads us to conclude that Ramage's (1987) explanation is most likely correct: the low winds are an artifact of changing sea state and Beaufort force scales.

It is interesting, and possibly instructive, that the problem addressed in this paper was uncovered in the course of attempts to use wind data products to simulate long time series of oceanographic variables. With sufficient confidence in the relevance of the ocean model physics, the discrepancies between simulated and observed sea level and sea surface temperature pointed out shortcomings of the wind dataset. The correction of these errors is obviously important for studies of climate. In addition, merchant ship reports continue to be an essential resource for the development and calibration of more sophisticated wind products, such as those now produced by operational weather forecasting centers, or those soon to be available from the spaceborne scatterometers ERS-1 and NSCAT.

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