Toward a Revised Beaufort Equivalent Scale

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Abstract

Using individual observations from the COADS Compressed Marine Reports 5 (CMR5), separate objective analyses of estimated and measured wind speed climatology for the global oceans during the period 1970-89 is produced. Fields of annual mean estimated/measured wind speeds are used to analyze the performance of four current Beaufort equivalent scales: a) WMO Code 1100, b) CMM-IV, c) Cardone, and d) Kaufeld. This analysis identifies major biases in these scales and a method is proposed to correct individual estimated wind observations in COADS. The sensitivity of this new method on different seasons, decades and individual oceans is discussed. It is shown that this new method produces consistent estimates of measured/estimated annual mean wind speeds over the global oceans with much reduced bias compared to calculations based on previous Beaufort equivalent scales. When compared to the old WMO Code 1100 Beaufort scale estimates, our method produces higher climatological wind speeds over the global oceans and removes the long term artificial trend, with the magnitude of such corrections higher in the boreal summer.

Introduction

The complex interactions between the ocean and the atmosphere are realized through fluxes of heat, momentum and fresh water at the ocean surface. Bulk aerodynamic parameterizations of these fluxes rely strongly on the determination of wind speed a few meters above sea level. This paper further documents shortcomings in wind speed observations by the Voluntary Observing Fleet (VOF) and proposes a simple method for correcting estimated wind reports in COADS. Details of the calculation are reported by da Silva et al. (1994). Here we summarize the main results of that paper.

Wind speed reported by the VOF are either directly measured with anemometers or estimated from sea state. Instrumentation problems with anemometers are believed (or better, assumed) to be nonsystematic and hopefully cancel out when spatial/temporal averages are taken. Although wind speeds are systematically related to anemometer height, standard surface layer similarity theory can be used to homogenize wind reports coming from ships with anemometers at different levels (e.g., Large and Pond, 1981). This homogenization, of course, requires the availability of anemometer height metadata for each wind report, which is not readily available at the moment. Following Cardone et al. (1990), an average anemometer height of 20 in is assumed throughout this study. Estimated winds are somewhat subjective and depend on the skill of the observer. Even when a correct identification of the sea state is made, the Beaufort estimate still needs to be converted to wind speed through a Beaufort equivalent scale. Since 1946 a Beaufort equivalent scale developed by Simpson (1906, 1926) combined with a well-defined description of sea state due to Petersen (1927) has been used for meteorological weather services (Isemer and Hasse 1991). This scale is commonly referred to as Code 1100.

The estimated speed included in the Comprehensive Ocean-Atmosphere Data Set (COADS) is based on the old WMO Code 1100 Beaufort equivalent scale. It is now widely accepted that the old WMO (Code 1100) Beaufort equivalent scale contains systematic errors and several alternative scales exist (WMO 1970, Cardone 1969, Kaufeld 1981, Ramage 1987).

In this study we use COADS individual reports to investigate the performance of four alternative Beaufort equivalent scales. Having documented climatological biases in all 4 current scales, we then introduce a very simple formula (eq. 6) to correct estimated wind speeds reported in COADS. The performance of this correction for individual oceans, seasons and decades is briefly discussed (details can be found in da Silva et al., 1994, and is followed by a discussion of the impact of our estimated wind speed correction on the long term climatology and wind speed trends. We start by describing the data source and method of analysis in the next section.

Data Source and Method of Analysis

Data set

The primary data source for this study is the Compressed Marine Reports 5, product 10 of the Comprehensive Ocean-Atmosphere Data Set-COADS/CMR5 (Slutz et al., 1985). Release 1 of COADS includes data from the late 1800's up to 1979. Recently these observations have been extended to the 1980's in the so-called interim product. The Release 1a of COADS that greatly improved the data set in the 1980's was not available in time for these calculations.

For each directly measured quantity available in CMR5/COADS (zonal and meridional wind components, air and sea surface temperature, sea level pressure, etc.) observations are rejected if they do not pass the trimming procedure with a threshold of 3.5 standard deviations as outlined in Slutz et al. (1985).

Estimated versus measured winds in COADS

Flag “WI” included in each COADS/CMR5 wind observation is used to discriminate measured from estimated winds. It should be noted that this flag takes only two values: 1 for measured winds and 0 for estimated winds or unknown. It is conceivable that some of the observations flagged as estimated/unknown could in fact be measured (see Cardone et al. [1990] for a discussion of problems with the measured/estimated indicator in a similar data set). In order to homogenize estimated winds, da Silva et al. (1994) found it necessary to bracket all COADS estimated wind speeds according to the old WMO scale (Table 1) and replace it with the appropriate equivalent wind speed.

Objective analysis

In order to eliminate spatial and temporal noise due to inhomogeneous sampling over the oceans we have objectively analyzed our fields to fill in gaps in data sparse regions and remove small scale noise. This is the same spatial resolution used in Levitus’ (1982) Climatological Atlas of the World Oceans. Objective analysis is also an effective outlier removal which is beneficial to the regression analysis of section 4. Details of the objective analysis can be found in da Silva et al. (1994) and Levitus (1982).

Assessing Current Beaufort Equivalent Scales

It is well established that the old WMO (Code 1100) Beaufort equivalent scale has systematic biases and that several alternative scales have been proposed. Although all these new scales confirm that the old WMO scale underestimates low wind speeds and overestimates high wind speeds (Fig. 4), they all differ in the precise amount. This section further documents the performance of these scales by comparing anemometer-measured winds with estimated winds based on each scale, in a climatological sense. The scales considered are WMO Code 1100, WMO CMM-IV (WMO 1970), Cardone (1969) and Kaufeld (1981).

Figure 1 plots estimated against measured northern hemisphere annual mean winds for the period 1970-1989, for each of the scales described above. Wind speeds estimated with Kaufeld’s scale have been converted from 25 m (average anemometer height in Kaufeld’s [1981] study) to 20 m, under the assumption of neutral stability. These scatter diagrams present several measures of error and goodness of fit, viz.

$$\text{std. dev.} = \left[\frac{1}{N}\sum_i (\overline{W}_{ei} - \overline{W}_{mi})^2\right]^{1/2} \qquad (1)$$

$$\text{bias} = \frac{1}{N}\sum_i (\overline{W}_{ei} - \overline{W}_{mi}) \qquad (2)$$

$$\text{scatter} = \left[\frac{1}{N}\sum_i (\overline{W}_{ei} - \overline{W}_{mi} - b)^2\right]^{1/2} \qquad (3)$$

where $\overline{W}_{ei}/\overline{W}_{mi}$ stands for climatological estimated/measured wind speed at gridpoint *i* and N is the total number of gridpoints. Figure 2 also shows the slope and intercept of the least square fit relating W_e to W_m in each panel.

Although the old WMO scale gives a slope very close to 1, it is clear from Fig. 2a that it underestimates wind speed with a standard deviation of almost 1 m/s. The CMM-IV Beaufort equivalent scale (Fig. 1b) does a better job for wind speeds in the range 5-9 m/s but tends to underestimate (overestimate) wind speeds greater (less) than 9 m/s (5 m/s). Kaufeld's scale (Fig. 1c), however, systematically overestimates wind speeds with a standard deviation of about 0.7 m/s and bias of 0.6 m/s. Like Kaufeld, Cardone's scale (Fig. 1d) tends to overestimate wind speeds less than 9 m/s, but does a much better job at higher values of the wind speed; both bias and standard deviations are about half those of Kaufeld.

Correcting Estimated Winds in COADS

Our main objective is to devise a correction to the Code 1100 Beaufort equivalent scale that would bring not only average measure/estimated wind speed in closer agreement, but also produce consistent average nonlinear quantities such as the average pseudo wind stress $\bar{P} = \overline{W^2} = \bar{W}^2 = \overline{W'^2}$. It is clear that a simple linear regression formula

$$W_{new} = x_1 W_{old} + x_2 \qquad (4)$$

would bring measured/estimated wind speeds in Fig. 5a in close agreement, as discussed in the previous section; in the above formula W_{new},W_{old} stands for the corrected and old WMO Code 1100 wind speed, and x_1, x_2 are constants to be determined. However, consistency between measured/estimated average pseudo wind stress $\bar{P}$ requires not only the mean speeds to be consistent ($\bar{W}_e = \bar{W}_m$), but also a consistency of standard deviations $\overline{W'^2_e} = \overline{W'^2_m}$ Such consistency of standard deviations cannot be accomplished with a simple linear regression. As discussed in the section above, a correction to the old WMO scale should increase low wind speeds and decrease high wind speeds. After much experimentation it was determined that such correction can be accomplished by a function of the form

$$W_{new} = x_1 W_{old} + x_2 \sqrt{W_{old}} \qquad (5)$$

All of the three alternative Beaufort equivalent scales of the last section can accurately be expressed in the form of eq. (5). The constants x_1, x_2 are determined by means of a least squares fit.

Figure 3 shows the results of these computations based on northern hemisphere data, base years 1970-89. Each “row” in this diagram corresponds to a different set of constants x_1/ x_2, and each “column” corresponds to test data for a particular period (annual, January or July). For example, the diagonal depicts estimated vs. measured wind speeds with the corrected Beaufort equivalent scale developed for that particular month.

It is clear from Figs. 3a,d,g that any of the new Beaufort equivalent scales performs better on climatological annual winds than the CMM-IV scale (Fig. 2b), the “best” among the current scales; the new January scale (middle row) performs nearly as well as the optimal annual scale with standard errors equal to 0.18 and 0.17 m/s, respectively (compare Figs. 5.a and 5.d). A close examination of Fig. 3 reveals that on January/July data the January scale comes slightly ahead of the annual scale. The July scale only outperforms the annual/January scales on the July data, but marginally so. The seasonal dependence of the scales is modest and does not warrant the use of a different scale for each month. Based on this analysis, and additional plots for other oceans, we selected the January scale as our primary scale. In this case eq. (5) reads:

$$W_{new} = 0.7870 W_{old} + 0.9547 \sqrt{W_{old}} \qquad (6)$$

Notice that when this equation is applied to climatological winds the second term on the RHS should be the average of $W_{old}^{1/2} (\overline{\sqrt{W}})$ rather than the square-root of the average wind $(\sqrt{\overline{W}})$.

The wind speed correction given in eq. (6) can be used to derive a revised Beaufort equivalent scale for use in COADS. In Table 1 the mean equivalent wind speed and respective interval of wind speeds for the WMO Code 1100 scale have been mapped using eq. (6) to produce a new corrected scale; this scale will be referred to as the UWM Beaufort climatological scale, because our method of correction is based on a climatological constraint rather than the usual method of paired observations. Figure 1 depicts the difference between this corrected scale and the other Beaufort equivalent scales. Consistent with the other scales, the UWM scale indicates that the old WMO Code 1100 scale underestimates low wind speeds and overestimates high wind speeds. However, the magnitude of the correction is generally smaller than previous alternatives to the old WMO scale.

Sensitivity Study

Da Silva et al. (1994) documents the regional temporal performance of the proposed wind speed correction in some detail. Only the main results are highlighted here.

Table 2 summarizes the relationship between measured/estimated wind speed in COADS for different months when our correction is applied. As expected, the best performance is attained for January, the base month used to derive the scale. Within 5% the results are consistent throughout the year.

Table 3 summarizes the performance of the UWM scale for 5 degree boxes around Ocean Weather Stations in the North Pacific and North Atlantic oceans. For each month from 1970 to 1989 separate monthly mean wind speeds are computed for measured and estimated wind reports. These boxes are chosen to include OWS so that a great number of anemometer measured reports are present. Monthly means with less than 30 observations for a particular month are eliminated. Notice that no objective analysis is performed. As before, the WI flag in COADS CMR5 was taken at face value, although H.-J. Isemer (personal communication) has brought to our attention apparent inconsistencies in this flag in the neighborhood of OWS. A sensitivity test eliminating dubious WI reports has been conducted and the main conclusions of this section are not affected by this tighter quality control. The most striking feature in Table

3 is the larger standard deviation (and scatter) compared to the climatological results presented in the previous sections. This increase in standard deviation is partially due to the absence of objective analysis, combined with the noisier character of monthly mean, regional data. Eleven out of the 16 boxes studied have slopes within 10% of one. Biases are generally small, although a few boxes (OWS B, E, N, and T) have biases in excess of 0.25 m/s. As an illustration of the results for a box with small slope and large intercept, Fig. 4 depicts measured vs. estimated wind speeds for the box around OWS P.

Figure 5 shows the global distribution of annual mean measured and estimated winds. Most of the large scale patterns of measured/estimated winds match quite well, surprisingly even in the data sparse regions of the southern oceans.

It is shown in da Silva et al. (1994) that our correction produces a consistent estimate of pseudo wind stress with a slope of 0.98 and small bias. However, there is a tendency to underestimate annual mean pseudo wind stress around 200 m^2/s^2.

Effect on Long Term Climatology and Trends

Figure 6 shows mean wind speed and standard deviation valid at 20 m for January, both corrected and the difference corrected minus uncorrected. In this calculation we used all quality controlled COADS data from 1945 to 1989, correcting all estimated wind speeds according to eq. (6). Consistent with previous studies, corrected speeds exceed uncorrected winds by about 0.5 m/s in parts of the North Atlantic, with smaller differences in the North Pacific. The corrected standard deviation (Figs. 6c,d) is reduced in the extra-tropics, with a more pronounced reduction (~ 0.3 m/s) in the North Atlantic ocean. The corrected standard deviation is generally increased in the tropics with magnitudes around 0. 1 m/s in the eastern tropical Atlantic and Pacific oceans. Similar calculations for the month of July are given by da Silva et al. (1994). Due to the lower wind speed in July, the correction to the wind speed (not shown) is positive and greater than for January for most of the globe. Consistent with the findings of Cardone et al. (1990), we note a reduction in the linear trend for most of the globe due to our scientific Beaufort scale correction (not shown). This artificial linear trend can adversely impact studies of long term variability of the ocean-atmosphere climate system.

Concluding Remarks

Using individual observations from the COADS Compressed Marine Reports (CMR5) we have produced analyses of wind speed climatologies for the global oceans during the period 1970-89. Computing climatological wind speeds based on (anemometer) measured and (sea state) estimated ship reports we have analyzed the performance of 4 current scientific Beaufort scales: a) WMO Code 1100, b) CMM-IV (WMO 1970), c) Cardone (1969), and d) Kaufeld (1981). Our analysis confirmed previous findings that the old WMO Code 1100 scale underestimates lower wind speeds and overestimates high wind speeds. Nevertheless, the other three so-called scientific Beaufort equivalent scales have biases of their own, with the CMM-IV being more accurate for intermediate winds (5-9 m/s). Having established the need for a new scale, we proposed the following formula to correct estimated wind speeds in COADS:

$$W_{new} = 0.7870 W_{old} + 0.9457 \sqrt{W_{old}}$$

where W_{old} is wind speed given in COADS based on WMO Code 1100 scale, and W_{new} is our corrected estimate at a 20 m reference level. Notice that the above formula is valid only for individual observations and cannot be applied directly to monthly mean wind speeds. Our proposed correction performs reasonably well for all seasons, and marginally so in the southern hemisphere, where the poor sampling gives considerably more scatter compared to the northern hemisphere. For the month of January, there is also a poor correspondence between measured/estimated wind speeds in the Indian ocean. Overall, the new scale produces higher wind speeds throughout the globe, and reduced standard deviations. The magnitude of such corrections is generally larger in July compared to January. In agreement with Cardone et al. (1990), the long term linear trend is reduced for most of the globe.

It is important to notice that the validity of our correction is dependent on the reliability of flag WI in COADS/CMR5. (Flag WI allows us to discriminate measured/estimated wind observations). Recently, S. Woodruff (personal communication) has brought to our attention results of some preliminary tests in which some wind reports flagged as measured were determined to be estimated. If such inconsistencies exist in COADS/CMR5 they have been incorporated in our scale, which effectively brings measured/estimated wind speeds into agreement. To settle this question detailed information about the reporting ships is required. Although in principle it is possible to compile some of this metadata, it is a formidable task and such information is not likely to be included in COADS in the near future. As more reliable data becomes available we will update our analysis to reflect these changes. In the meantime, we claim that the corrections proposed in this paper produce a more consistent estimate of COADS wind speed over the global oceans.

Acknowledgments

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Table 1: **Equivalent wind speed and intervals for WMO Code 1100 Beaufort equivalent scale and UWM Beaufort climatological scale.**

		WMO Code 1100			UWM		
Beaufort Number	Descriptive Term	Interval of equivalent wind speed		Mean equivalent wind speed	Interval of equivalent wind speed		Mean equivalent wind speed
		knots	m/s	m/s	knots	m/s	m/s
0	Calm	0 - 1	0.0 - 0.2	0.0	0 - 2	0.0 - 1.0	0.0
1	Light air	1 - 3	0.3 - 1.8	0.8	3 - 5	1.1 - 3.0	1.5
2	Light breeze	4 - 6	1.9 - 3.3	2.4	6 - 8	3.1 - 4.5	3.4
3	Gentle breeze	7 - 10	3.4 - 5.4	4.3	9 - 13	4.6 - 6.7	5.4
4	Moderate breeze	11 - 16	5.5 - 8.5	6.7	14 - 18	6.8 - 9.7	7.7
5	Fresh breeze	17 - 21	8.6 - 11.0	9.4	19 - 23	9.8 - 12.0	10.4
6	Strong breeze	22 - 27	11.1 - 14.1	12.3	24 - 28	12.1 - 14.9	13.0
7	Near gale	28 - 33	14.2 - 17.2	15.5	29 - 34	15.0 - 17.7	16.0
8	Gale	34 - 40	17.3 - 20.8	18.9	35 - 40	17.8 - 20.9	19.0
9	Strong gale	41 - 47	20.9 - 24.4	22.6	41 - 46	21.0 - 24.1	22.4
10	Storm	44 - 45	24.5 - 28.6	26.4	47 - 54	24.2 - 27.8	25.7
11	Violent storm	56 - 63	28.7 - 32.7	30.5	55 - 60	27.9 - 31.4	29.3
12	Hurricane	64	32.8	34.9	61	31.5	33.1

Table 2: **Performance of the UWM Beaufort climatological scale (base month: January) applied to data from several months. Slope, intercept, standard deviation (σ) and scatter are defined in section 3, equations (1) - (3).**

month	slope	intercept	σ	bias	scatter
January	0.99	0.07	0.35	-0.00	0.35
April	1.03	-0.21	0.34	0.01	0.34
July	0.95	0.34	0.36	-0.01	0.36
October	1.02	-0.20	0.40	0.04	0.40
Annual	1.03	-0.24	0.18	0.01	0.18

Table 3: **Interannual performance of the UWM scale near Ocean Weather Stations. Data are unanalyzed monthly means for 5° x 5° boxes around Ocean Weather Stations. Estimated/measured paris are included only if more than 30 wind observations occur for each month. The period covered id 1970 - 89 with the maximum number of data points being 240. Slope, intercept, standard deviation (σ) and scatter are defined in section 3, equations (1) - (3).**

Nearby OWS	5° x 5° box center		No. months	slope	intercept	σ	bias	scatter
A	62.5°N	32.5°W	98	0.56	4.02	1.27	0.07	1.47
B	56.5°N	50.5°W	36	1.09	-1.20	1.48	0.34	1.44
C	52.5°N	35.5°W	170	0.79	2.10	1.18	0.03	1.18
D	44.5°N	40.5°W	199	0.92	0.84	0.96	-0.04	0.96
E	35.3°N	47.5°W	215	0.91	0.56	0.93	0.26	0.89
I	59.5°N	18.5°W	133	0.95	0.58	1.32	-0.06	1.32
J	52.5°N	19.5°W	155	0.93	0.60	1.03	0.12	1.02
K	45.5°N	15.5°W	215	0.95	0.48	0.73	-0.02	0.73
L	57.5°N	19.5°W	224	0.89	0.94	1.17	0.18	1.15
M	66.6°N	2.5°E	95	0.93	0.62	1.26	0.05	1.26
N	30.5°N	139.5°W	235	0.93	0.25	0.83	0.29	0.78
P	50.5°N	144.5°W	227	0.74	2.68	0.88	-0.03	0.88
R	47.5°N	16.5°W	214	0.96	0.48	0.82	-0.04	0.82
T	29.5°N	135.5°E	223	0.79	1.29	1.03	0.39	0.95
V	34.5°N	164.5°E	180	0.95	0.58	1.10	-0.06	1.10
X	39.5°N	153.5°E	206	0.78	2.12	0.96	-0.10	0.95

Table 4: **January scale applied to annual NH data by region.**

Region	slope	intercept	σ	bias	scatter
N. Atlantic	1.04	-0.34	0.15	0.01	0.15
N. Pacific	1.01	-0.12	0.17	0.01	0.17
S. Atlantic	1.11	-0.79	0.26	0.01	0.26
S. Pacific	1.00	0.04	0.31	-0.05	0.30
Indian	1.08	-0.46	0.27	-0.10	0.25
Tropics	1.03	-0.23	0.22	-0.00	0.22

Figure 1: The old WMO Beaufort scale (Code 1100) and four alternative scientific Beaufort scales; CMM-IV (WMO(1970), Cardone (1969), Kaufeld (1981) and our new scale (UWM).

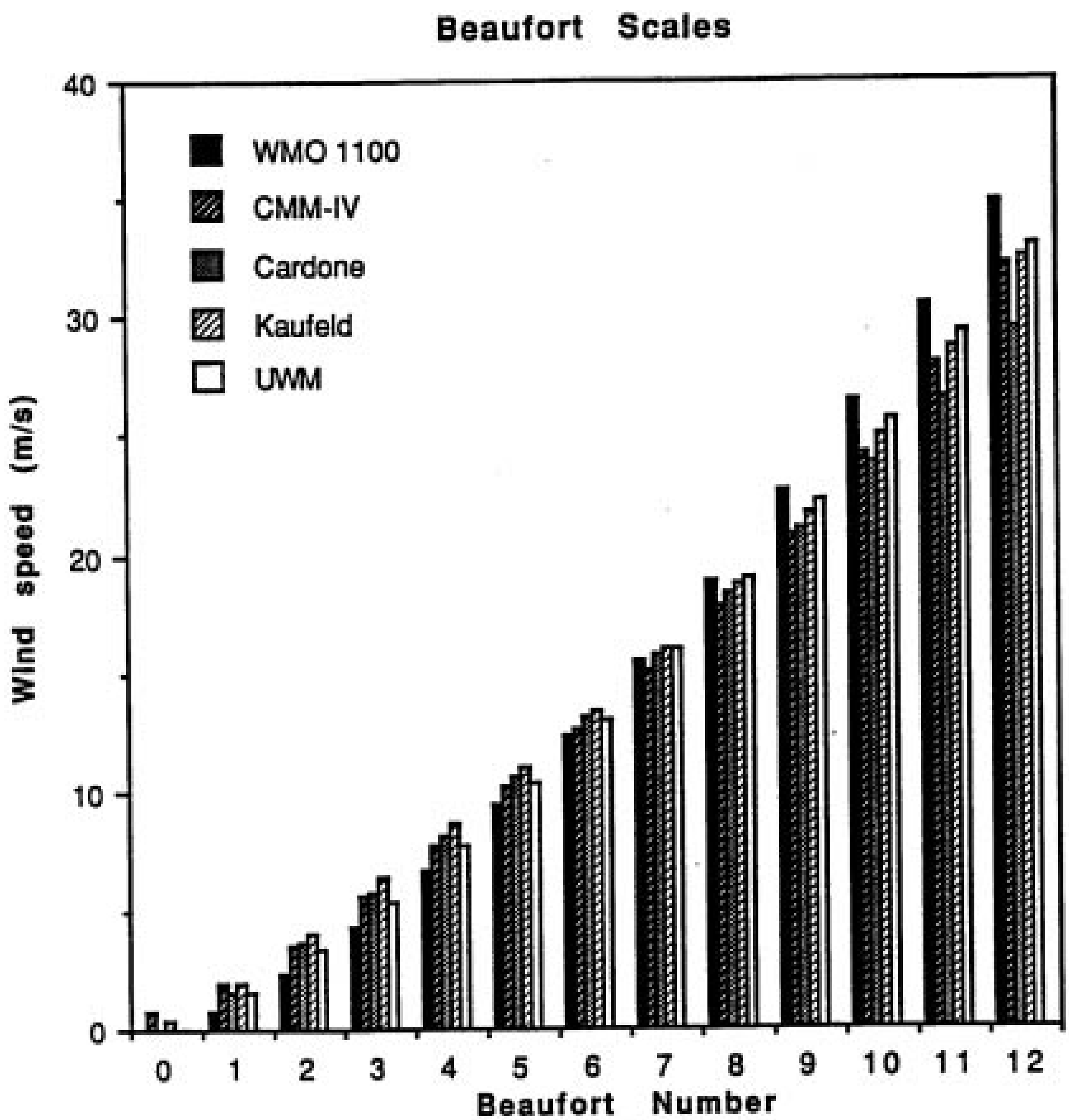

Figure 2: Analyzed estimated versus measured winds (annual mean, northern hemisphere) with estimated winds based on several equivalent Beaufort scales: a) old WMO (Code 1100), b) CMM-IV (WMO, 1970), c) Kaufeld (1981) and d) Cardone (1969). Each point in this diagram corresponds to measured/estimated winds on grid point over the northern hemisphere oceans; the horizontal grid spacing is 1° longitude by 1° latitude.

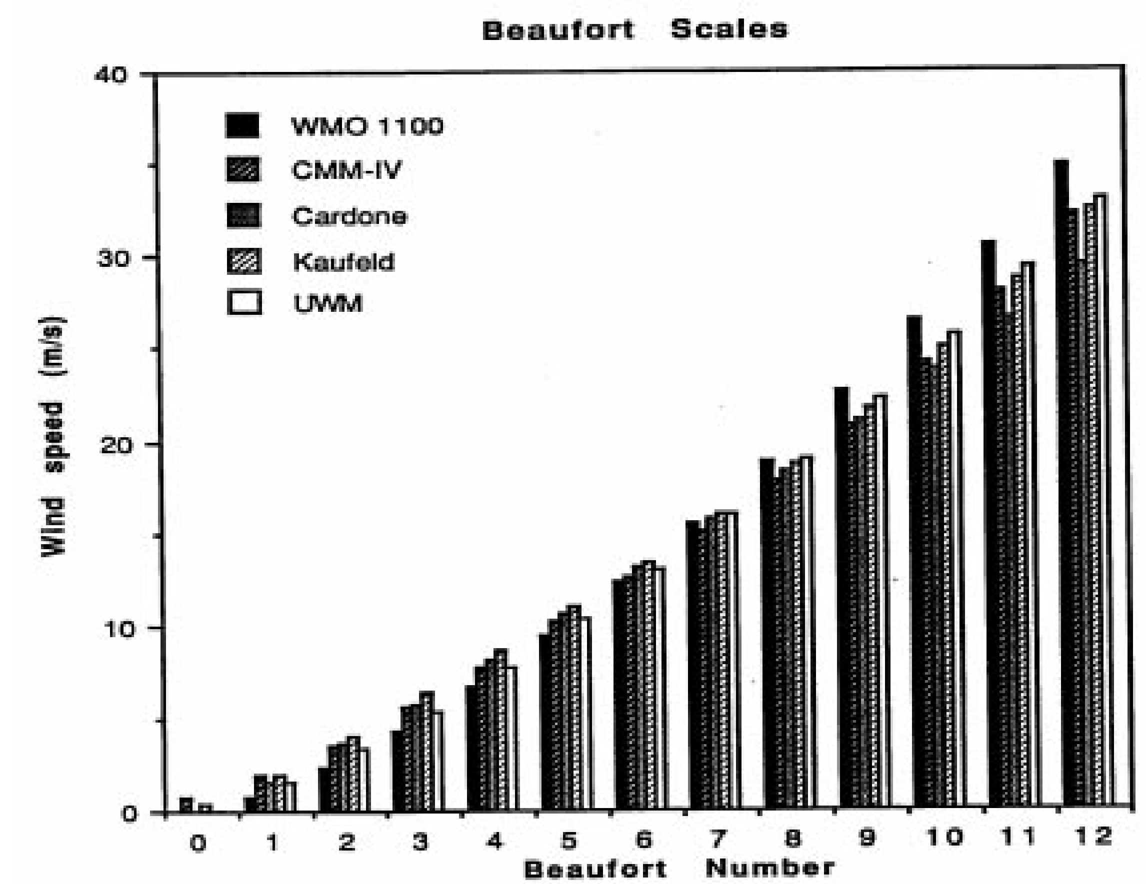

Figure 3: Analyzed estimated versus measured winds (northern hemisphere) with estimated winds based on several versions of our new Beaufort scale; a) the scale is developed based on annual mean data and used for annual mean estimated winds; b) as in a) but the scale is used on January mean data; c) as in a) but the scale is used on July mean data; d) the scale is developed based on January mean data and used for annual mean estimated winds; e) as in d) but the scale is used on January mean data; f) as in d) but the scale is used on July mean data; g) the scale is developed based on July mean data and used for annual mean estimated winds; h) as in g) but scale is used on January mean data and i) as in g) but the scale is used on July mean data.

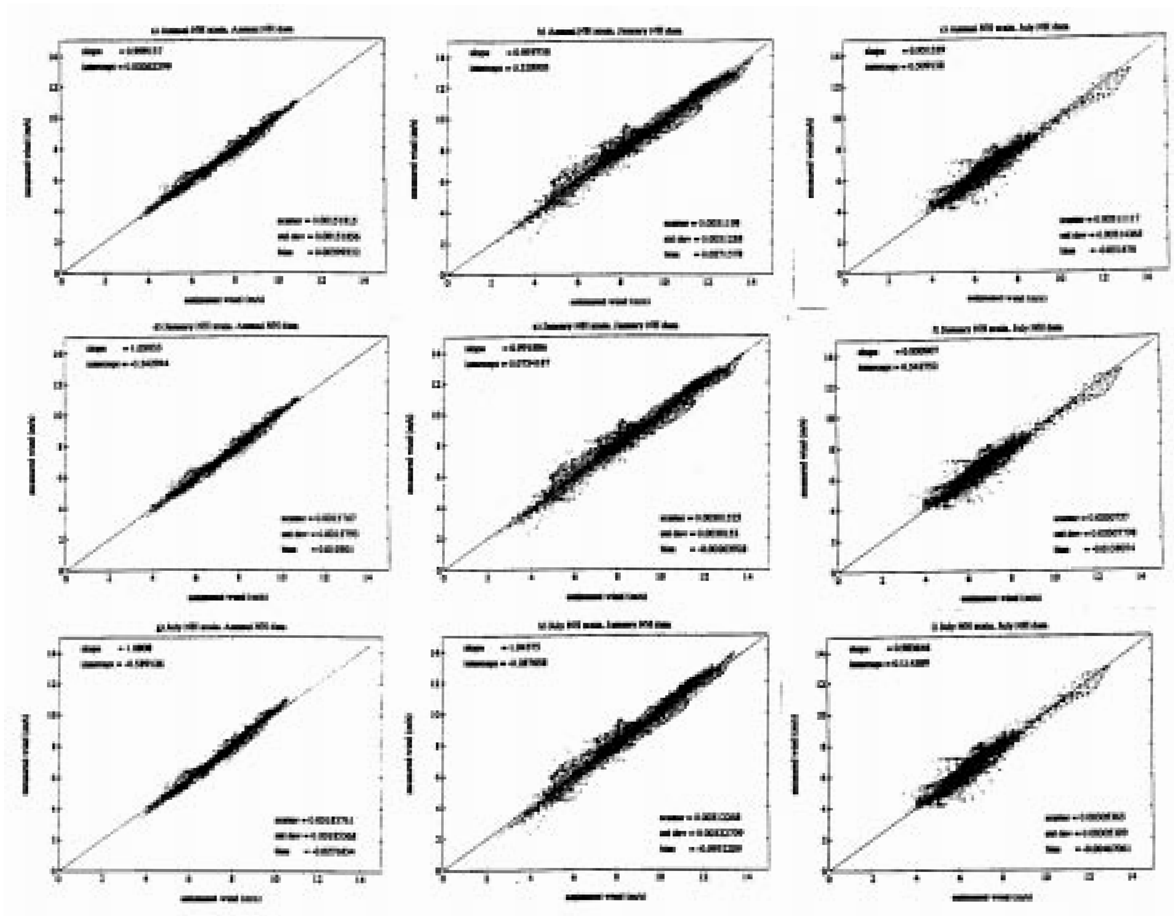

Figure 4: Estimate vs. measured winds for a 5 degree box around Ocean Weather Station Papa. Each dot corresponds to a monthly mean period 1970-89 in which more than 30 observations of each type were made inside the box.

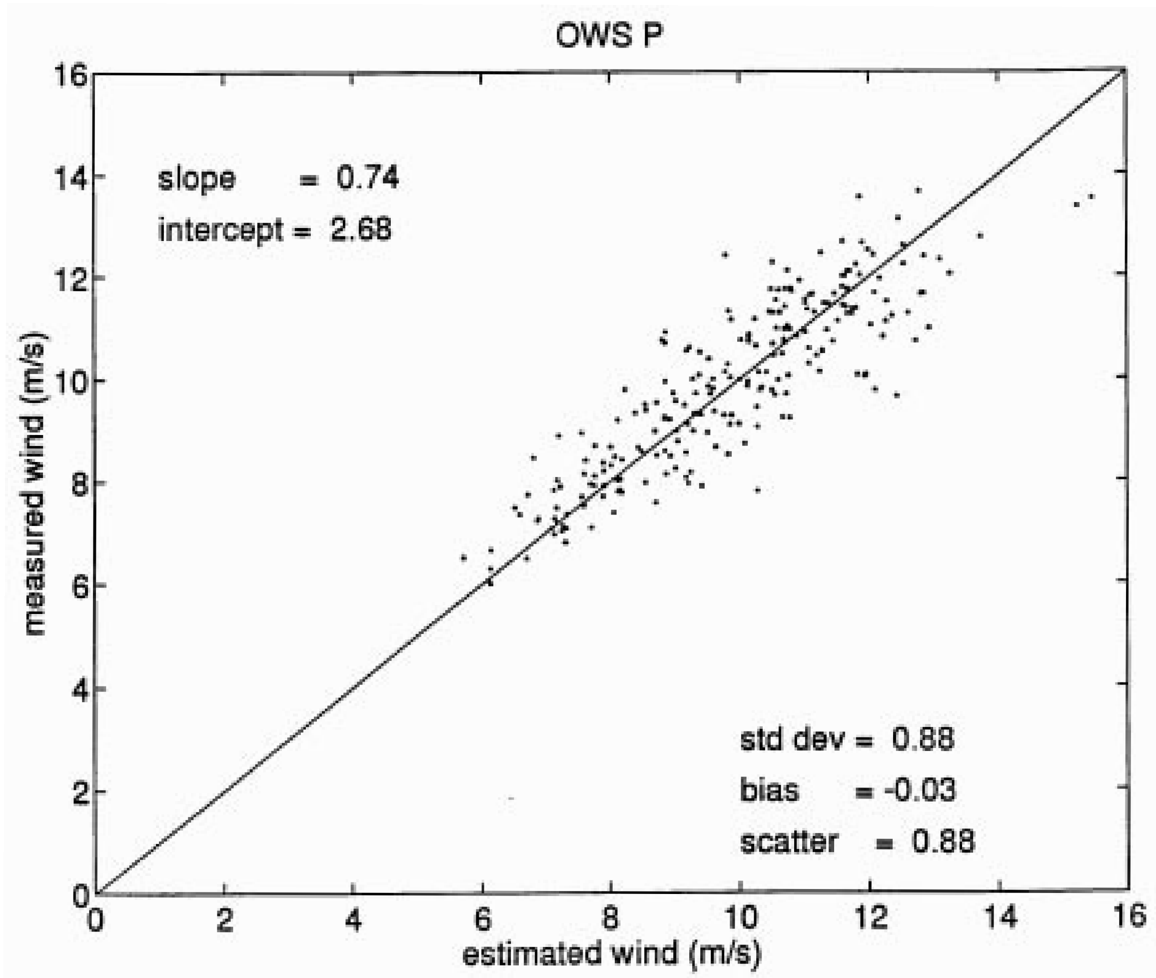

Figure 5a: Analyzed annual estimated wind speeds over the global oceans. Our new beaufort equivalent scale has been used to produce the estimated winds. Contour interval 1 m/s.

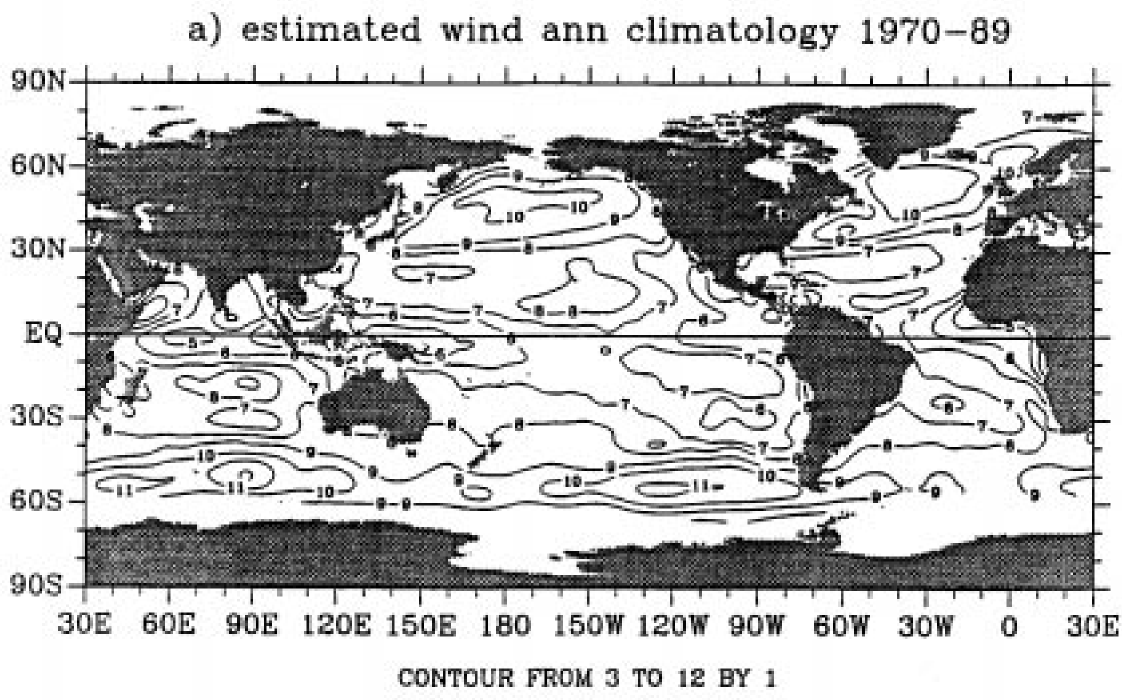

Figure 5b: Analyzed annual measured wind speeds over the global oceans. Contour interval 1 m/s.

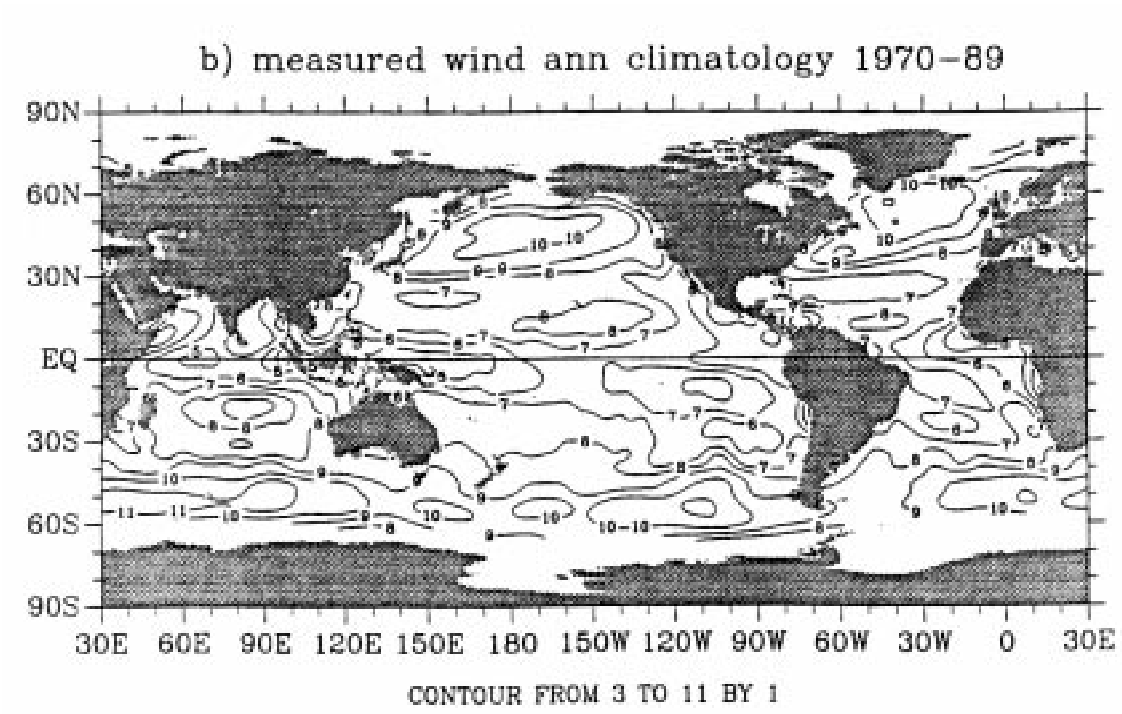

Figure 6a: January mean wind speed (1945-89) over the oceans, including both measured and estimated corrected winds; (contour interval: 1 m/s).

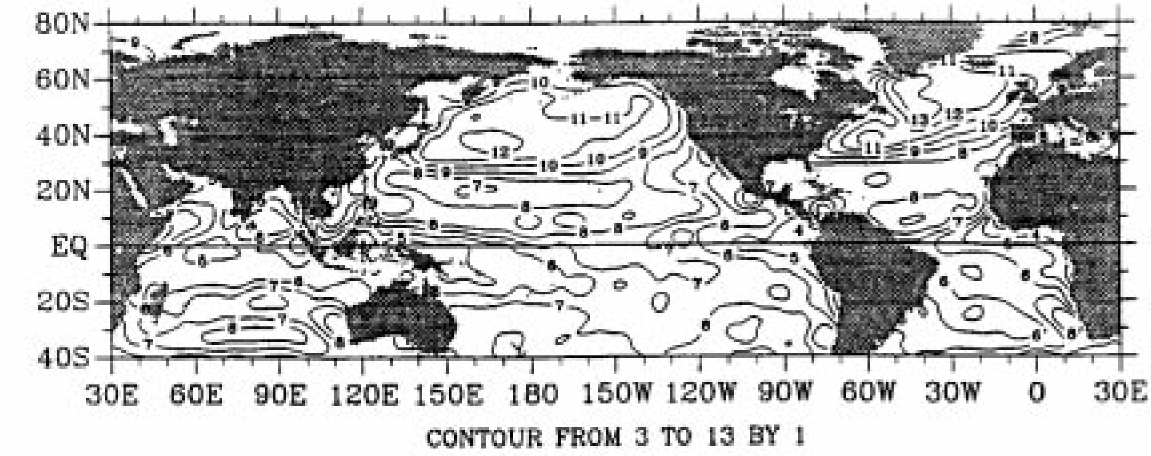

Figure 6b: January mean wind speed difference between corrected and reported wind speeds in COADS; (contour interval: 0.1 m/s).

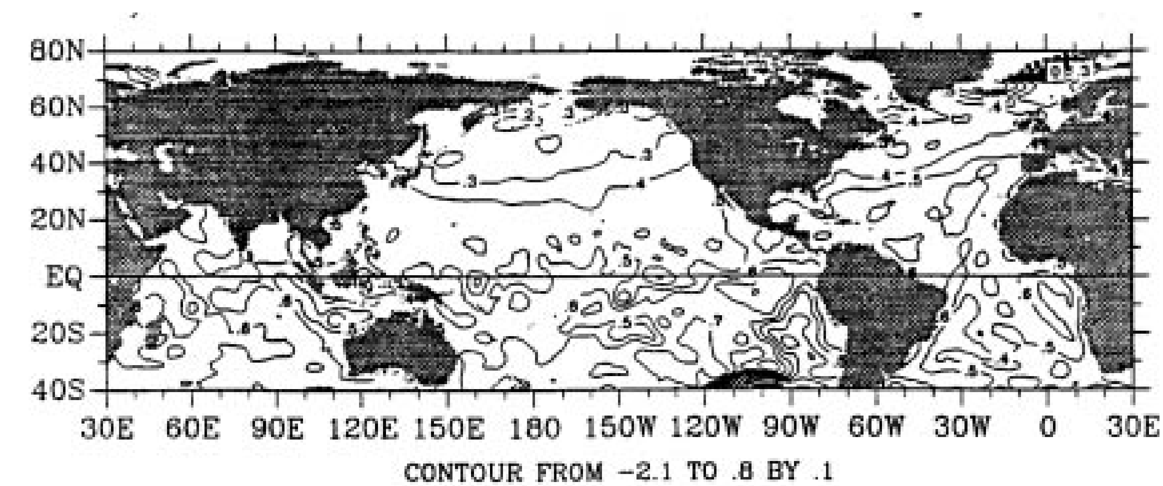

Figure 6c: January wind speed corrected standard deviation (1945-89) over the oceans, including both measured and estimated winds (contour interval: 0.5 m/s).

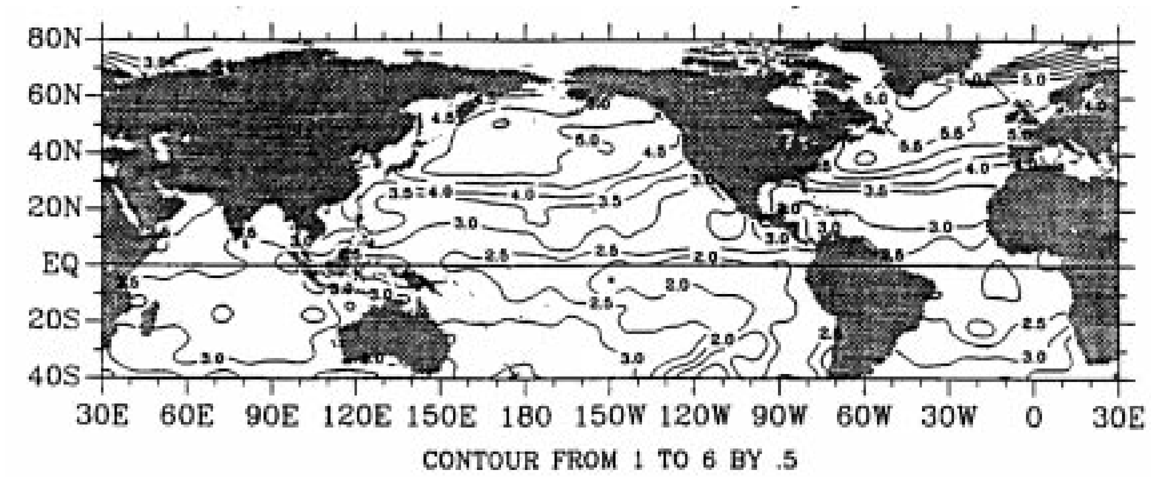

Figure 6d: January standard deviation difference between corrected and reported wind speeds in COADS (contour interval: 0.1 m/s).