A New Beaufort Equivalent Scale

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Abstract

By comparing Beaufort estimates with simultaneous wind speed measurements the relationship between both parameters can be determined in form of a Beaufort equivalent scale. Previous equivalent scales were derived without regard to the fact, that the error variances of the basic observations are different. In most cases, the variance of only one parameter minimized, either the variance of the Beaufort estimated or the variance of wind measurements. Such regression methods do not yield the universal relationship between both parameters, which is required for an equivalent scale.

Therefore a new Beaufort equivalent scale is derived by comparing the three-hourly wind speed measurements from six North Atlantic Ocean weather stations between 1960 and 1971 with more than 300,000 Beaufort estimates of passing merchant ships. But these two raw data sets are not comparable without regard to the different structure of error variances.

Firstly the random observation errors of the estimates and of the measurements are calculated to separate the error variance from natural wind variability in both data sets. In this way it can be shown that, as expected, the measurements from ocean weather stations are much more accurate than wind estimates. The difference in accuracy can be quantified. Secondly, daily means of wind speed from the measurements of the stationary ocean weather ships and spatial means from simultaneous estimates of surrounding merchant ships within an averaging area are computed. The latter comprise more individual observations than the means of ocean weather ships, so that the effects of the different observation accuracies are compensated. The radius of averaging areas are calculated separately for each season and each region, so that the spatial variability within this area is equal to the temporal variability at the ocean weather station within 24 hours. Only such pairs of averaged observations are suitable, because neither random observation errors nor natural variability has a falsifying effect. On these especially generated data pairs the method of cumulative frequencies, which allows one to detect also non-linear relationships, is applied in order to obtain the optimal Beaufort equivalent scale.

Introduction

Today a large portion of wind observations at sea is still reported in terms of Beaufort force. Beaufort estimates are made subjectively and based on the visual appearance of the sea surface (Petersen, 1927). But the usual parameterizations of interactions between ocean and atmosphere need the information of the metric wind speed 10 in above sea level. Therefore, a Beaufort equivalent scale, which attaches a wind speed value to each Beaufort step, is of great importance especially for the study of air-sea fluxes (Isemer &Hasse, 1991).

Since about 100 years many attempts have been made to determine the universal relationship between Beaufort force and wind speed. In any case, equivalent scales are evaluated by comparing Beaufort estimates with neighboring wind measurements. The regression line, based on such pairs of observation, yields the requested equivalent scale. But there are at least two ways to calculate a regression line: either by minimizing the variance of the Beaufort estimates while considering the measurements as independent parameter, or, conversely, by minimizing the variance of the wind speed. The first method yields the regression of Beaufort on wind speed, the second the regression of wind speed on Beaufort

It is well known, that these two one-sided regressions are useful to predict the most probable value of the wind speed for a given individual Beaufort estimate, and vice versa. But this is not, what an equivalent scale should perform. An equivalent scale should give the universal relationship between both parameters. In principle, this relationship is defined by the orthogonal regression, lying exactly between the two one-sided regressions. However, the error variances of both parameters have to be equal, otherwise the best equivalent scale is tilted to the more accurate parameter.

These considerations are rather old. At the end of the last century Köppen proposed, firstly in a publication of Waldo (1888), to consider the wind speed as independent and to average the Beaufort force. Other researchers followed him, and it became customary to use the regression of Beaufort on wind speed as equivalent scale. The most famous example for this kind of evaluation is the Code 1100, originally derived by Simpson (1906). This old WMO scale (Fig. 1) is still in use.

In contrast, since about 1945 most scales have been based on the reverse regression: the wind is averaged for each Beaufort number (Roll, 1951; Verploegh, 1956; Richter, 1956; WMO, 1970). Consequently, the regression of wind speed on Beaufort is obtained. The accordance of nearly all modem scales in their relatively low slope does not prove the shortcoming of the old WMO scale. The reason for the difference is simply the use of different regression methods. Neither method is absolutely correct for deriving an equivalent scale. However, the old method, averaging the estimates, is better, if the measurements are more accurate. (Actually they are, which is shown subsequently.) In any case it is impossible to derive a correct equivalent scale without knowledge of the error variance in both parameters.

Data

Individual wind observations from six Ocean Weather Ships (OWS) in the North Atlantic and from neighboring Voluntary Observing Ships (VOS) were taken from COADS (Fig. 2). In order to derive a Beaufort equivalent scale, wind measurements and estimates have to be separated to be able to compare measurements from OWS with estimates from VOS. However, the only information in COADS concerning the kind of observation is a flag, indicating whether the wind is measured or whether the observation method is unknown. Additionally, this flag seems to be not very reliable. (Isemer and Lindau, 1994). For this reason all wind observations from OWS are assumed to be measured without regard to the flag. All VOS reports, flagged as unknown, are assumed to be Beaufort estimates.

In COADS direct information about Beaufort force is only available in some decks. The standard information concerning the wind force is given in knots, even if the wind was originally estimated. Obviously the wind speed was obtained by converting the estimates with the old WMO scale Code 1100. In the following computations these knot-values will be used, because averaging Beaufort numbers is difficult due to the nonlinear character of the Beaufort scale.

In this study the period from 1960 to 1971 is considered. The fifties and sixties were the decades with the largest number of OWS in the North Atlantic. The evaluations are restricted to an even more limited period, because there are indications of a time-drift of the scale. Therefore, first an equivalent scale has to be developed for a certain, relatively short period. After that, a calibration with pressure gradients allows to calculate a time dependent scale. The latter was done in another study, also published in this volume.

Error Variances of the Observations

As mentioned above, it is necessary to know the magnitude of the observation errors in both parameters, in measurements and in the estimates, before deriving an equivalent scale.

The random error variance of Beaufort estimates from VOS is calculated in the following way. Pairs of simultaneous observations are formed within the VOS data set. The difference in wind speed between two ships is computed, squared and summed up, separately for 50 different classes from 10 km to 500 km. In this way the mean total variance of the observed wind is obtained as a function of distance Δx (Fig. 3). Two factors contribute to the variance: on the one hand true natural wind variability, in this case pure spatial variability because the observations are simultaneous, and on the other hand random observation errors. Of course the total variance is growing with increasing distance, reflecting the spatial wind variability. At the distance $\Delta x=0$ no natural wind variability remains, so that here the total variance consists exclusively of the error variance σ_o^2. The σ_o^2 cannot be calculated directly, because two ships cannot be in the same place at exactly the same time. However, an estimate of σ_o^2, may be obtained by a linear fit for the total variance and extrapolating to $\Delta x=0$. In this way an error variance $\sigma_o^2 = 47\ kn^2$ results. As variances of differences between two observations, respectively, are considered, the value of σ_o^2 comprises the inaccuracy of two ships. Therefore σ_o^2 has to be divided by two to get the mean error variance of a single ship. Thus, the mean error variance of wind observations from merchant ships can be estimated to 23.5 kn^2.

In order to obtain the error variance of OWS measurements, the procedure is repeated with simultaneous pairs consisting of one VOS observation and one OWS observation, respectively (Fig. 4). Now, the total variance increases faster with distance than in the first case, when VOS-VOS pairs were considered. This is due to the fact, that OWS are measuring the wind speed about 25 m above sea level, while the WMO scale Code 1100, which was used to convert the VOS estimates, is defined for a height of 10 m. Therefore, there is an additional reason for wind speed differences between OWS and VOS. Not only natural wind variability and observation errors, but also a different reference level contributes to the variance. It can easily be shown, that this effect increases with distance.

In order to exclude the effect of different reference levels, individual OWS measurements are reduced from 25 m to 10 m, by assuming a logarithmic wind profile and using drag coefficients according to Large and Pond (1981). The stability is taken into account and a constant relative humidity of 80% is supposed. After the reduction the slope of the linear fit for OWS-VOS pairs is equal to the increase for VOS-VOS pairs (Fig. 5). The variance at the distance $\Delta x=0$ amounts to 34.3 kn^2, representing the sum of mean observation errors at OWS and at VOS. As VOS errors are already calculated, an error variance of 10. 8 kn^2 is obtained for wind speed measurements at OWSs.

Since OWS measurements have proved to be more accurate than Beaufort estimates made on merchant ships, the optimal equivalent has to ascend even steeper than the orthogonal regression, if Beaufort is plotted at the abscissa. Thus, the old method proposed by Köppen is not exactly correct, but quite reasonable compared to the usual technique applied nowadays.

Method

With the knowledge of both error variances, there remains no major obstacle on the way to an equivalent scale. In this study the method of cumulative frequencies is applied. The proceeding is as follows: both data sets are sorted separately in ascending order. In this way the exceedance probability for each value in both distributions is known. Values with the same exceedance probability in their respective distribution are considered to be equivalent. For linear relationships this procedure is identical to the orthogonal regression, but it allows one to detect also non-linear relationships, as they are expected, between Beaufort and wind speed.

Intending to apply the method of cumulative frequencies the different error variances in OWS measurements and VOS estimates have to be equalized. This is attained by averaging the individual observations. VOS means are based on a larger number of wind reports than OWS means, so that the difference in accuracy is compensated. However, only a few values are assembled for each mean, so that sufficient variability remains between them.

Not only error variances in both parameters must be equal, but also the mean natural variability which is included in the averages. For example, monthly means are not at all comparable to 10-minute means. In this regard a problem appears because of the different structure of OWS and VOF data. Measurements from stationary OWS have to be averaged in time, but merchant ship reports have to be averaged in space. Therefore, corresponding spatial and temporal averaging radii have to be defined.

While OWS measurements were always averaged over 24 hours, the corresponding spatial averaging radius for VOS was computed for each season and each region. Figure 6 shows for example the evaluations at the vicinity of OWS I in autumn. First, the error variance of OWS is computed analogous to the method described in Section 3, but taking time lags instead of spatial distances. This value is subtracted from the total measured variance to obtain the true natural variability within 24 hours. Taking now the VOS data, the error variance is computed too, and the natural variability can be separated. Then the radius is searched, where the pure spatial variability is equal to the pure temporal variability within 24 hours deduced from OWS data. In most cases a radius between 300 and 400 km results.

The New Scale

We are now able to derive an equivalent Beaufort wind scale. Daily means of OWS measurements are compared to spatial means of observations from neighboring merchant ships, within the averaging radius evaluated above. OWS means are always based on 4 individual reports. VOS means are calculated, if at least three simultaneous observations are available. The VOS means are based on about 6 individual reports in average. These averages fulfill two conditions: (1) their mean accuracy is equal and (2) they contain the same natural variability.

The method of cumulative frequencies yields the new Beaufort equivalent scale (Fig. 7 and Table 1). Actually, the old WMO scale Code 1100 is calibrated, because the COADS knot-values, which are based on this scale, are used for the computations. The new scale is valid for a height of 25 m, since this is the OWS anemometer level. The general features of the new scale, compared to the Code 1100, are considerable higher values for the most frequent Beaufort numbers. This is not at all surprising, because the new scale is valid for 25 m instead of 10 m.

An alternative scale is derived using reduced OWS measurements. The wind speed reduction from 25 m to 10 m was carried out as described previously. Figure 8 shows the resulting l0 m-scale. The equivalent values of this new scale are rather similar to the old WMO scale code 1100 for the most frequent Beaufort numbers 2 to 6. Their trifling rise compared to the old WMO scale is compensated by considerable lower values for the stronger and less frequent Beaufort numbers. This result confirms entirely the previous consideration concerning the regression methods: it is true, the Code 1100 curve ascends slightly too strong if equivalent values are plotted against Beaufort number, since measurements are of course not totally accurate. However, the old WMO scale is not at all as insufficient as most of the newer derivations suggest, because the accuracy of measurements, at least at OWS, is much better than the accuracy of Beaufort estimates.

Applications of the Scale

If the new Beaufort scale is well derived, wind speed measurements of OWS should coincide with converted estimates of surrounding merchant ships. In this manner, the new 25 m-scale is tested. Individual monthly means within an area of 5° latitude and 7° longitude are evaluated from VOS data by using the new scale. They are compared to monthly means of the OWS, which is situated in the center of the area. This is carried out for the period 1960 to 1971 for the selected area surrounding the six OWS, which are used for the derivation. For such comparisons the orthogonal regression has to be used, because error variances of monthly means, based on several hundred individual reports, are negligibly small. Figure 9 shows the almost optimal agreement of OWS measurement and converted VOS estimates.

This result is not totally trivial. Only a relatively small part of the VOS data was used to derive the new scale, in order to satisfy the requirements with regard to the variances. The test proves, that the restricted sample is representative for the whole data.

Some further remarks are necessary concerning the application of the new scale. In order to compute fields of wind stress the squared wind speed v^2 has to be evaluated. But observation errors affect the results as follows. A wind speed observation V may be divided into the true part v and an observation error Δv according to:

$$V = v = \Delta v \qquad (1)$$

Consequently, the mean pseudo stress $[V^2]$, calculated simply from the observations, contains not only the true value $[v^2]$, but also the error variance $[\Delta v^2]$.

$$[V^2] = [v^2] + [\Delta v^2] \qquad (2)$$

Thus, as a matter of principle, calculating wind stress is impossible, if the observation error of the wind speed is unknown. This holds true, if the calculations are based on Beaufort estimates. In this case the error variance of the converted estimates has to be ascertained. Since the scale recommended in this study is derived by separating natural variability and error variance, the effect of observation inaccuracy is easy to calculate. It is exactly the error variance which was computed for merchant ship observations in an earlier section.

Universality of the Scale

Further equivalent scales are derived for different meteorological conditions, for example stability-dependent and seasonal scales (Fig. 10). The differences are small, so that the conversion of all wind estimates with only one universal scale is possible without great errors.

Unfortunately, the nations of the merchant ships are not registered in COADS until the year 1970. In order to derive special scales for each nation a data set from Seewetteramt Hamburg is used. These observations show, that different nations estimate the wind's force very differently.

In average American Beaufort estimates are about 2 knots higher than neighboring German observations! Consequently national equivalent scales are quite different (Fig. 11). For this reason, a multi-national scale which is derived in the North Atlantic cannot be transferred into a region with another nation-mix, like the Pacific ocean. In order to convert Beaufort estimates of COADS, it would be very helpful, if the nationality of the ships were available, so that the different national scales could be applied.

Summary

Evaluations of the error variance for OWS measurements and for VOS estimates show, that wind measurements on board of OWS are much more accurate. Paying attention to the different observation errors and also taking care for comparable natural variability in both data sets, a new equivalent scale results, which is not very different to the old WMO scale Code 1100. The similarity is due to the fact, that the regression method used in former times was very reasonable: In contrast to the present, the more accurate wind speed measurements were considered as an independent parameter.

Strictly speaking, the recommended scale is valid only in the North Atlantic and for the period 1960 to 1971. A transfer in time is attainable by using gradients of air pressure. A transfer in space seems to be possible without problems, because special scales for different meteorological situation are rather similar. However, the obvious differences in estimating wind force between different nation raise some problems, if the scale is transported in regions with other prevailing countries of origin. For a careful conversion of Beaufort estimates different scales should be used for different nations.

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Table 1: New Beaufort equivalent scale, valid for a height of 25 m above sea level.

Bft	0	1	2	3	4	5	6	7	8	9	10	11	12
knots	0.0	2.3	5.4	9.5	15.0	20.5	25.5	30.9	36.8	43.2	50.6	58.9	68.8

Table 2: Mean scalar wind speed difference between VOS estimates compared to simultaneous and neighbouring (up to 150 nm) measurements from OWS.

Nation	Former SU	USA	France	United Kingdom	FR Germany	Nether-lands
Δu kn	0.0	-0.3	-1.2	-1.5	-2.0	-2.3

Figure 1: The old WMO scale Code 1100 compared to the scientific Scale of the WMO CCM IV. The old scale is based on the regression of Beaufort on wind speed, the latter on the regression of wind speed on Beaufort.

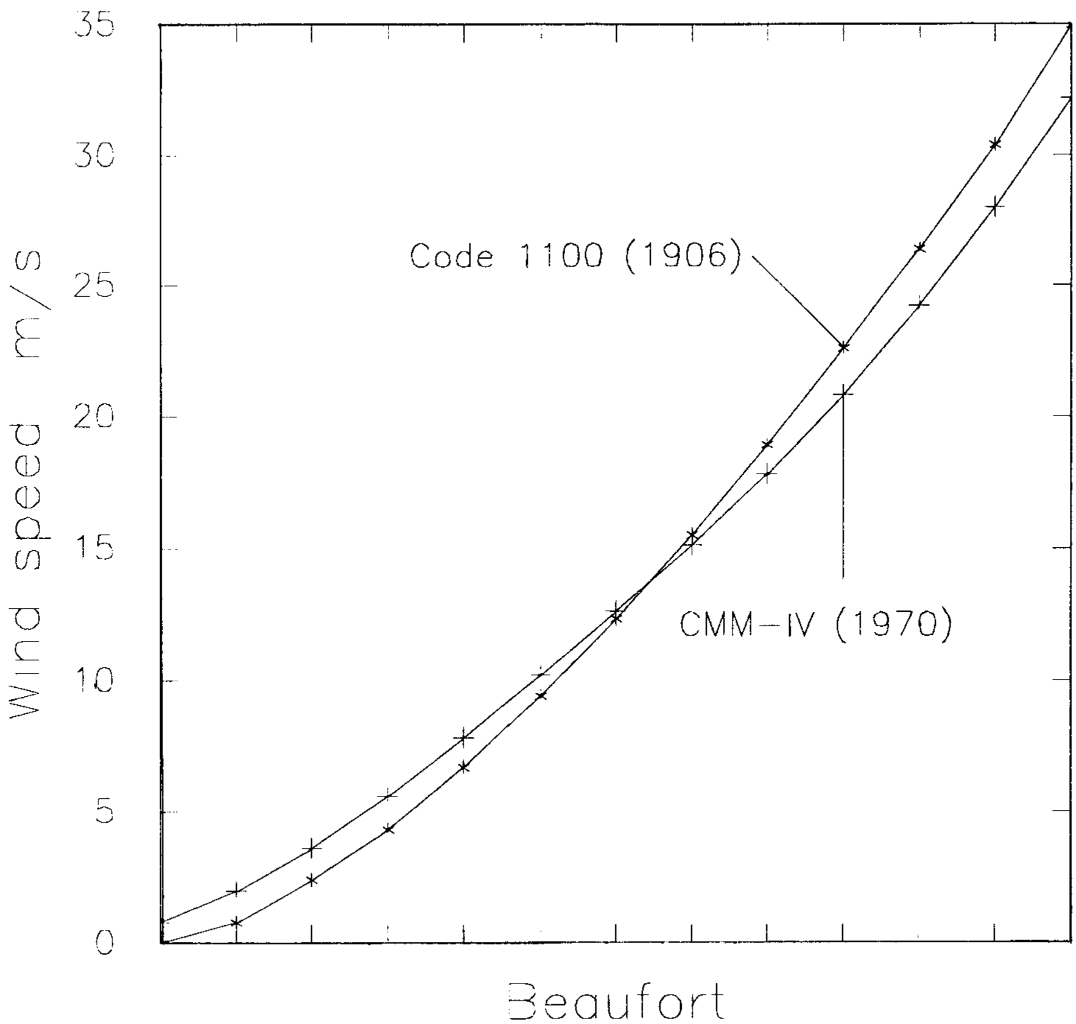

Figure 2: Locations of six North Atlantic ocean weather stations. Their wind speed measurements were used to derive a new Beaufort equivalent scale.

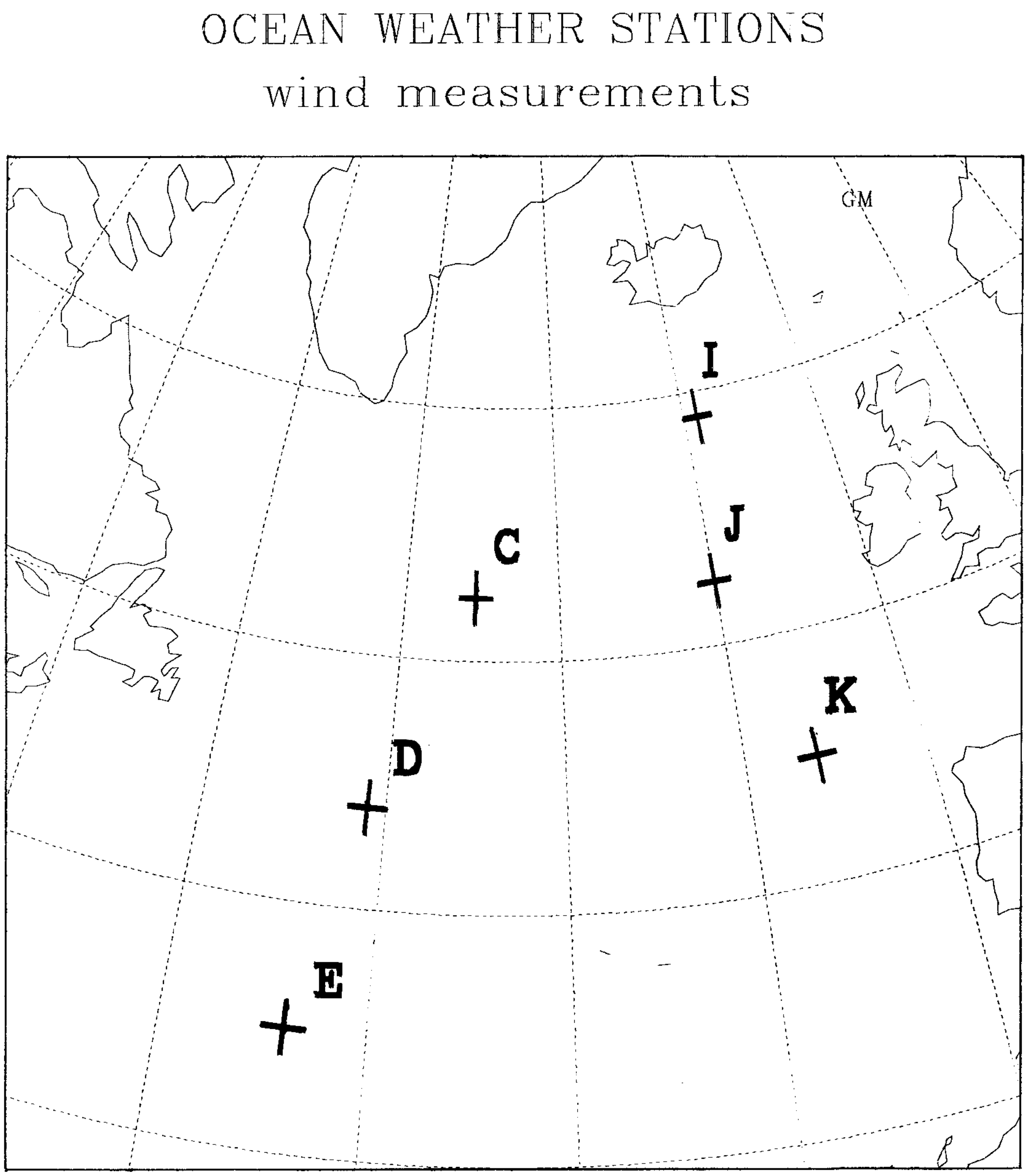

Figure 3: Mean squared difference of wind speed as a function of distance. The results are based on pairs of VOS-VOS estimates.

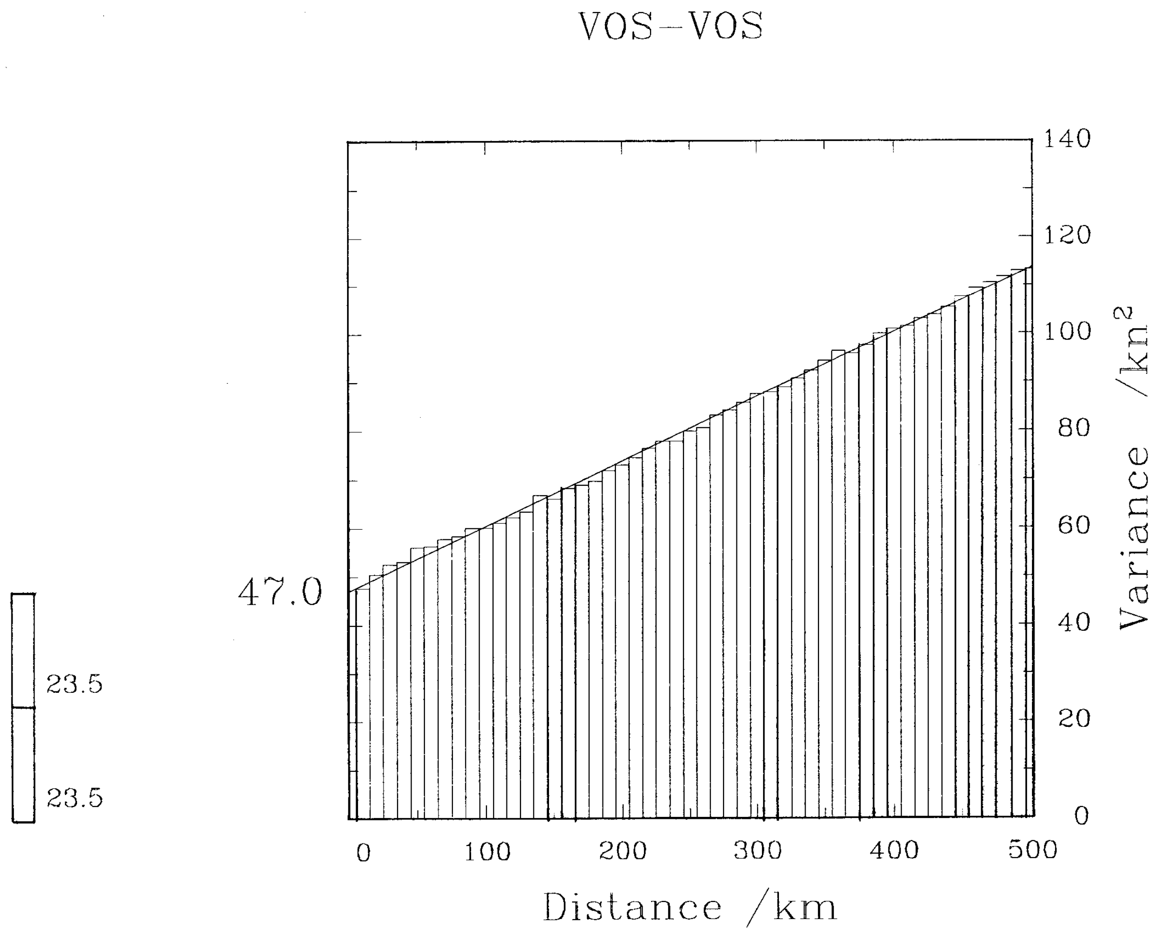

Figure 4: As Fig. 3, but additionally the results for pairs of OWS-VOS as hached portion of the bars. The measurements of OWS are not reduced.

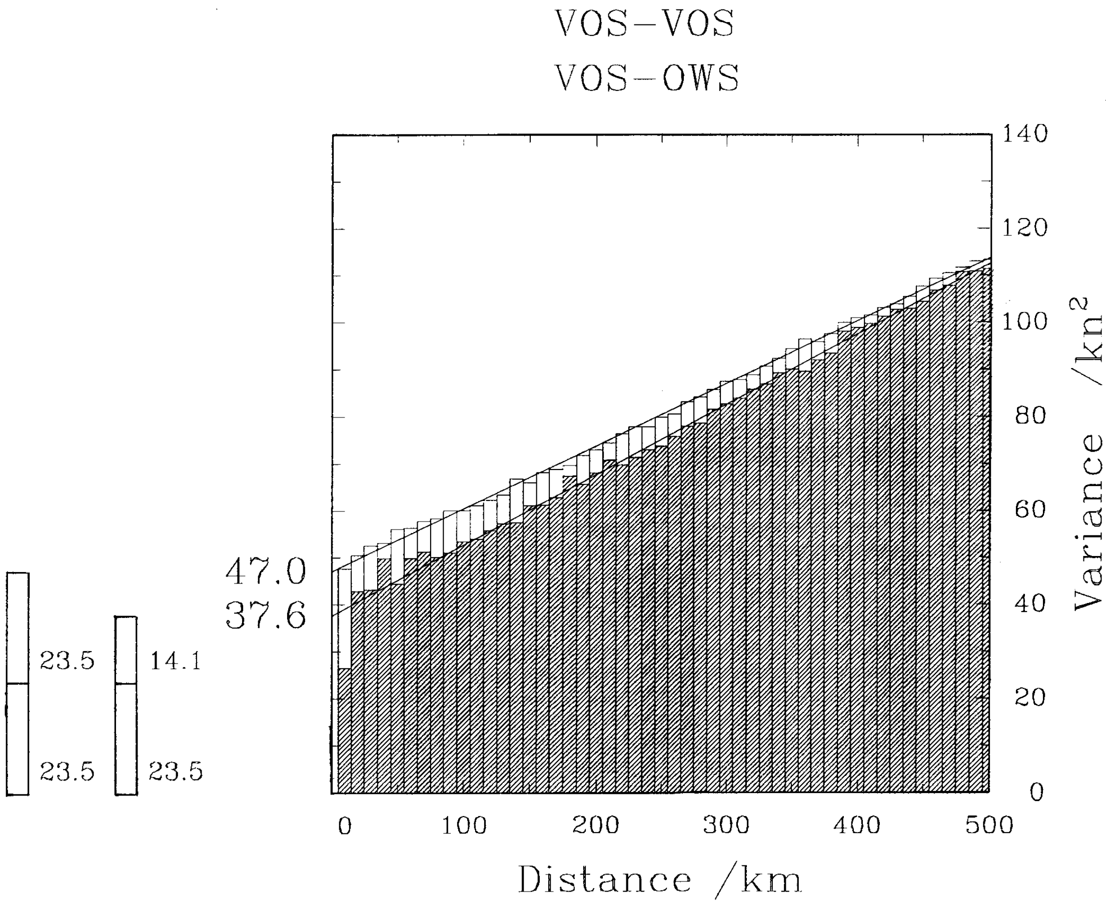

Figure 5: As Fig. 4, but the measurements of OWS are reduced from 25 m to 10 m.

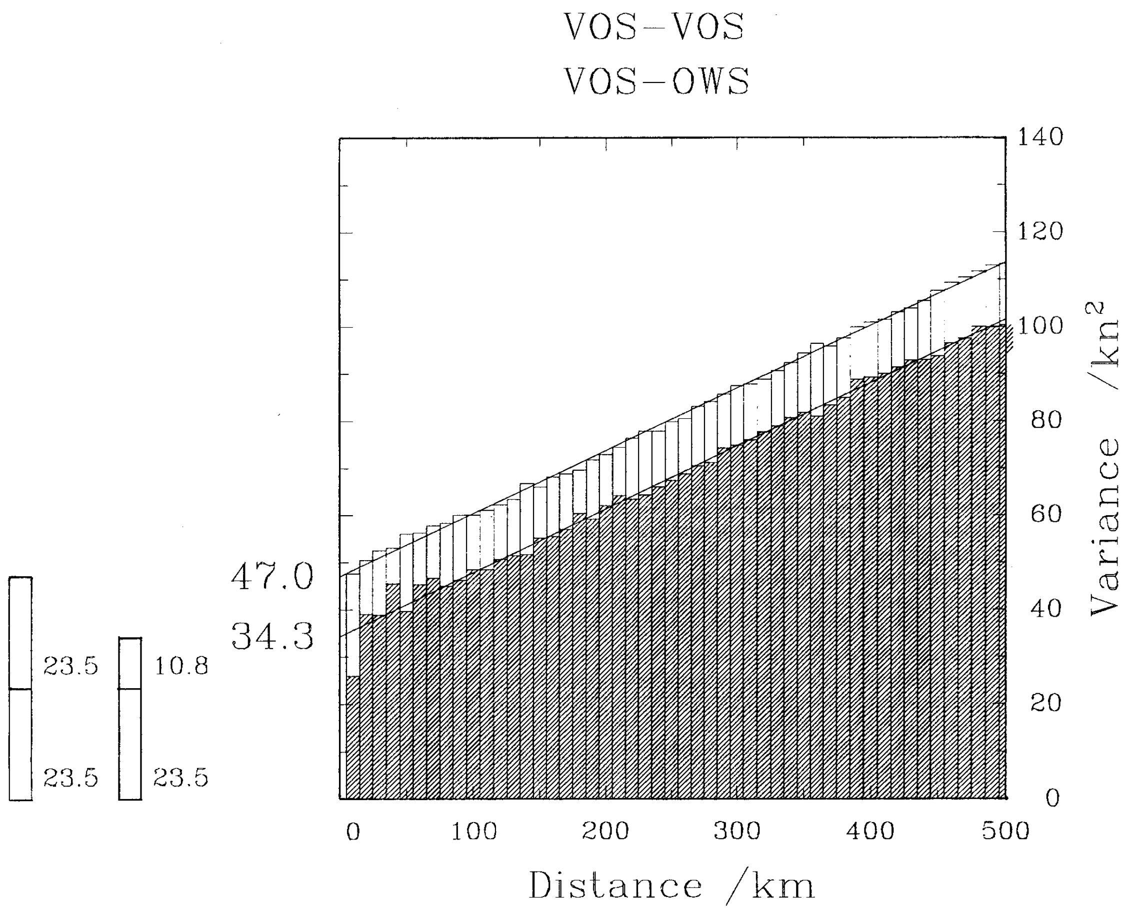

Figure 6: Illustration of computing the averaging radius, examplified by the season autumn in the vicinity of OWS I.

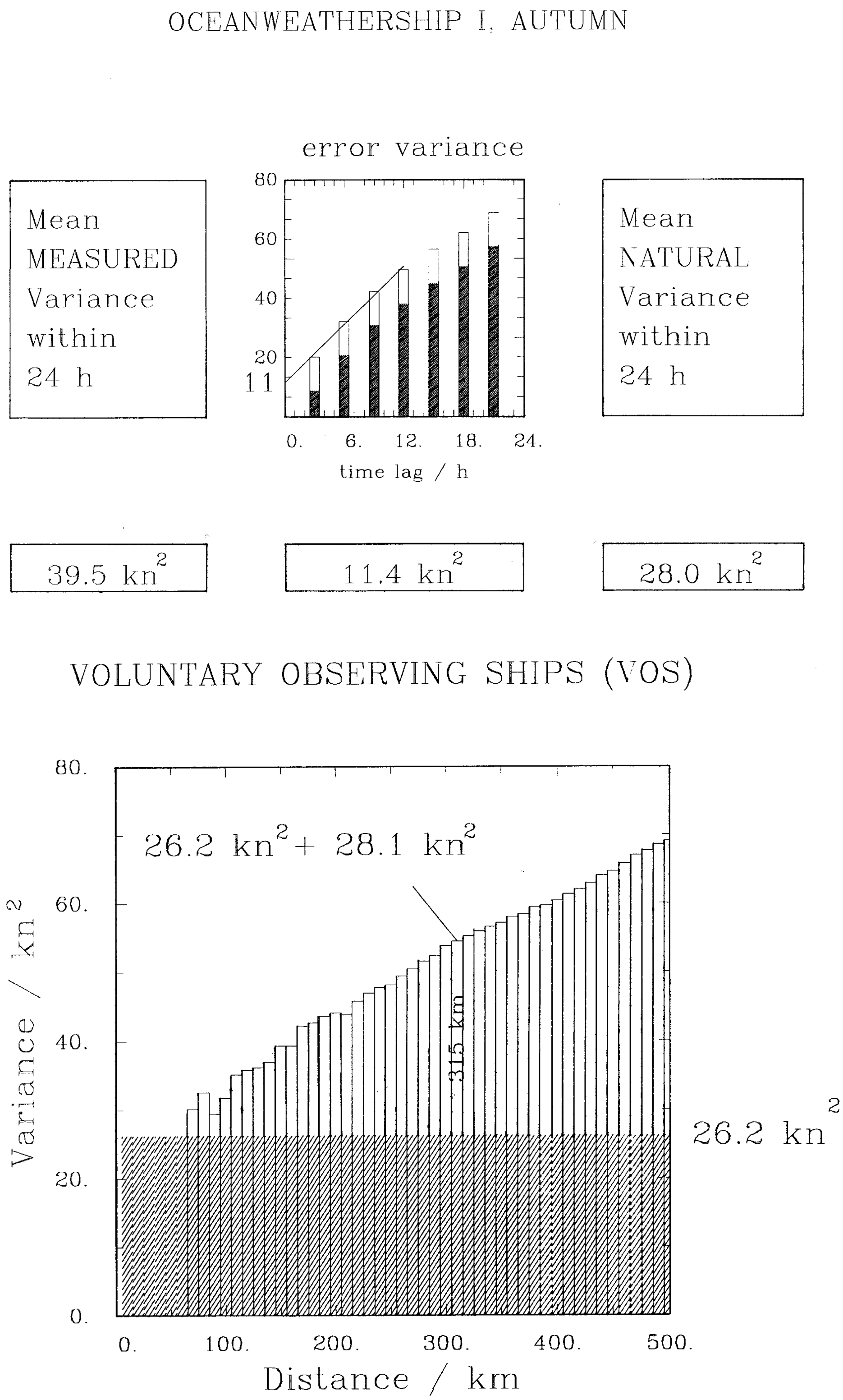

Figure 7: New Beaufort equivalent scale valid for a height of 25 m above sea level.

BFT	0	1	2	3	4	5	6	7	8	9	10	11	12
WMO	0.0	1.7	4.7	8.4	13.0	18.3	23.9	30.2	36.8	44.0	51.4	59.4	67.7
NEU	0.0	2.3	5.4	9.5	15.0	20.5	25.5	30.9	36.8	43.2	50.6	58.9	68.8
N	6	378	2287	8441	17197	11598	8870	4655	2068	597	122	15	1

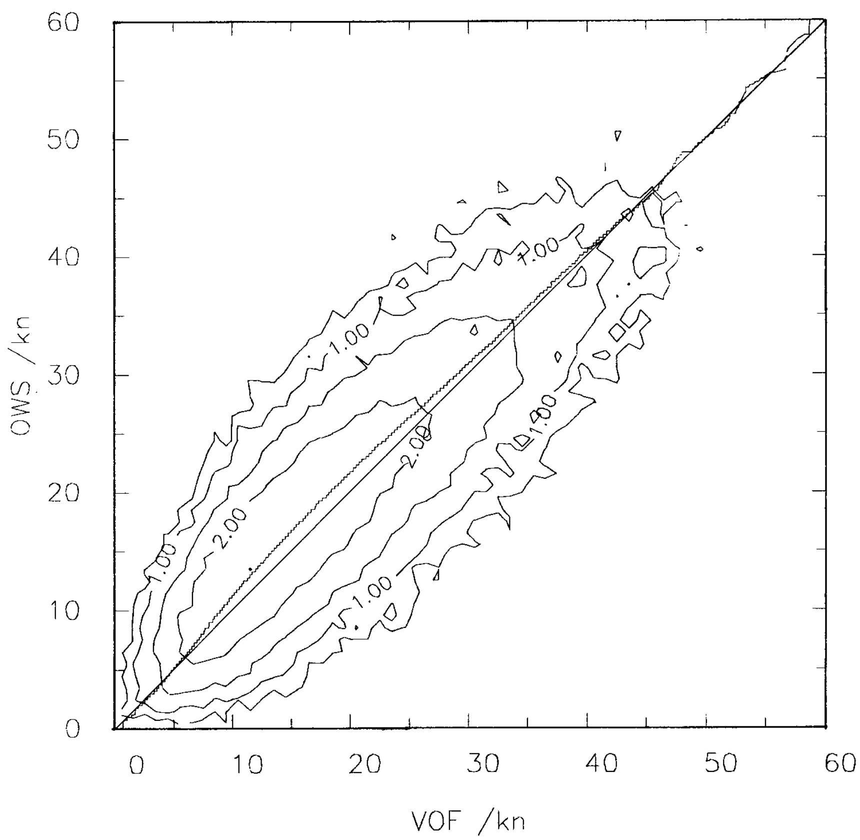

Figure 8: New Beaufort equivalent scale based on reduced OWS measurements, therefore valid for a height of 10 m.

BFT	0	1	2	3	4	5	6	7	8	9	10	11	12
WMO	0.0	1.7	4.7	8.4	13.0	18.3	23.9	30.2	36.8	44.0	51.4	59.4	67.7
NEU	0.0	2.3	5.2	8.9	13.9	18.9	23.5	28.3	33.5	39.2	45.5	52.7	61.1
N	6	378	2287	8441	17197	11598	8870	4655	2068	597	122	15	1

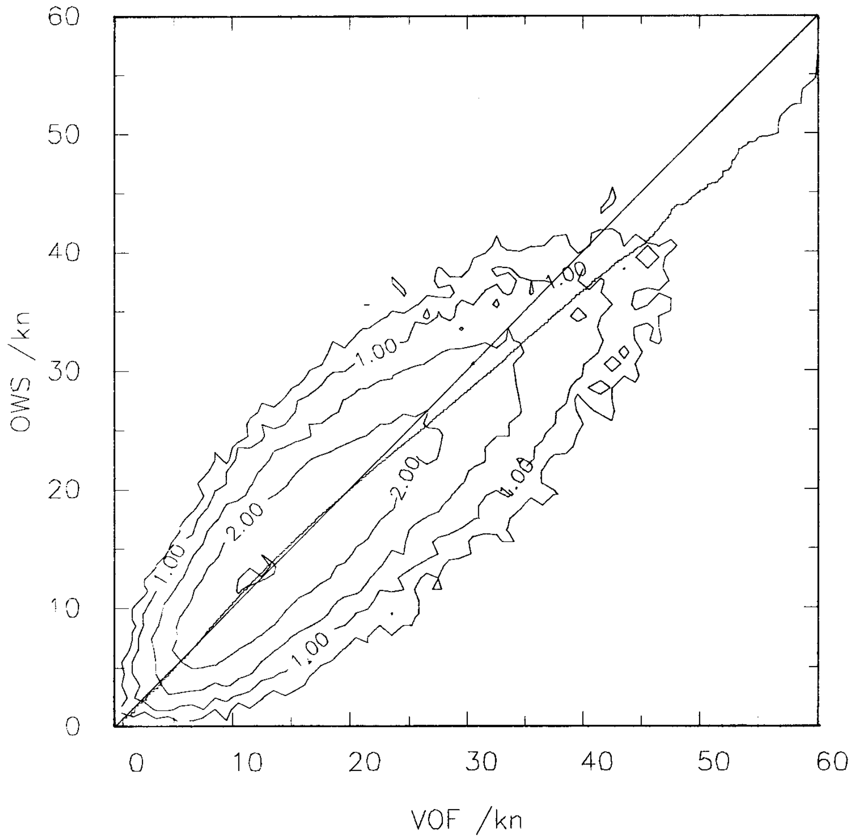

Figure 9: Individual monthly means of the wind speed in the North Atlantic from 1960 to 1972. In order to test the new 25 m-scale converted Beaufort estimates of VOS are compared to OWS measurements. VOS estimates are taken from a 5° x 7° area surrounding the respective OWS.

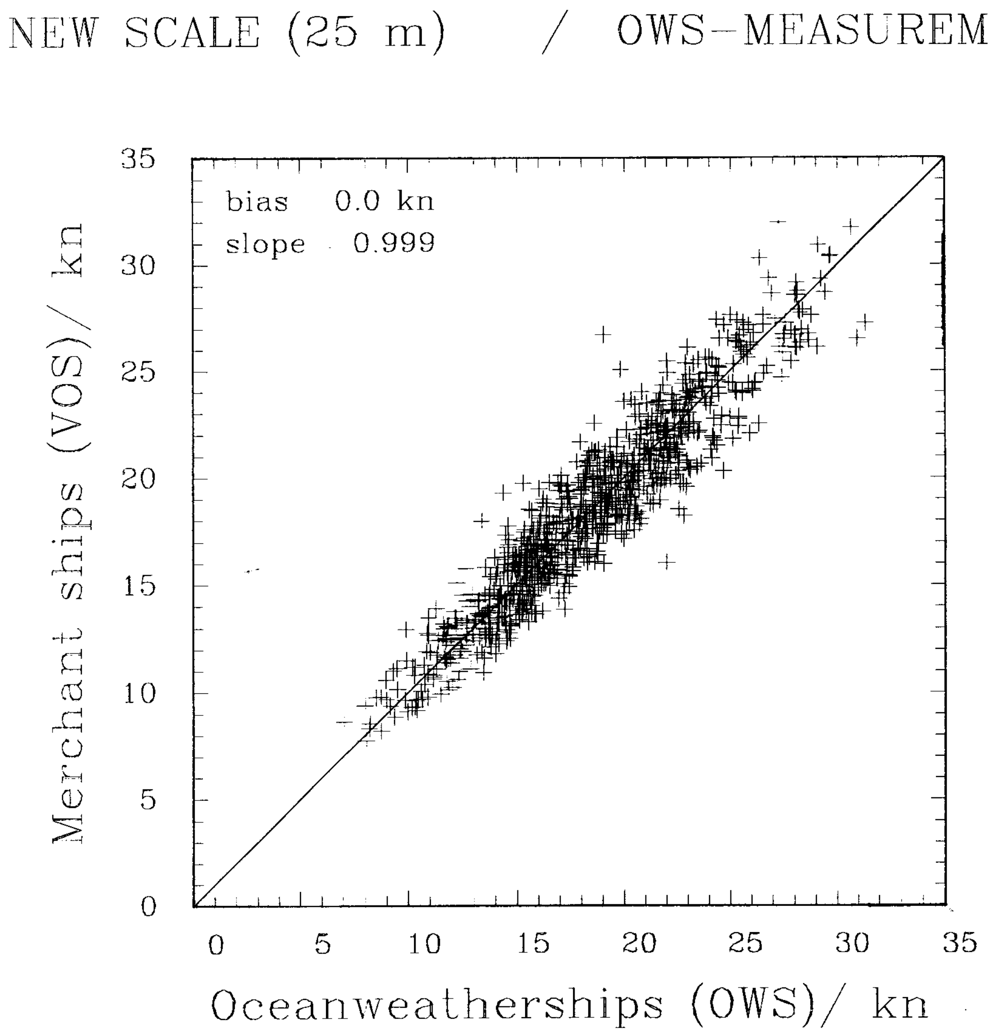

Figure 10a: Beaufort equivalent scales derived separately for each season. Differences to the proposed universal scale are figured.

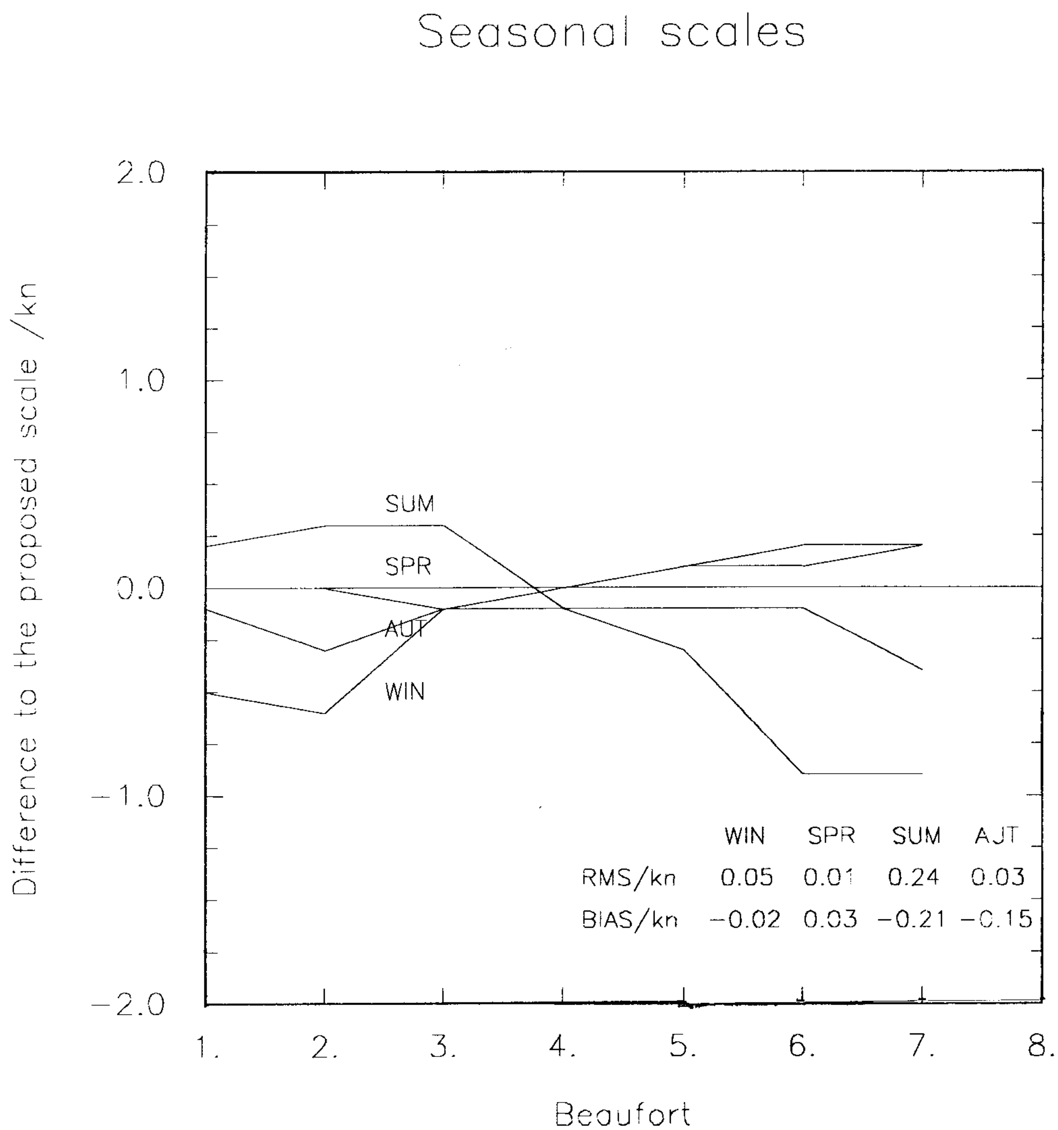

Figure 10b: As Fig. 10a, but for (1) instability and (2) stability or near neutral conditions, respectively. The critical value to separating both conditions is a temperature difference of -1 K between air and sea.

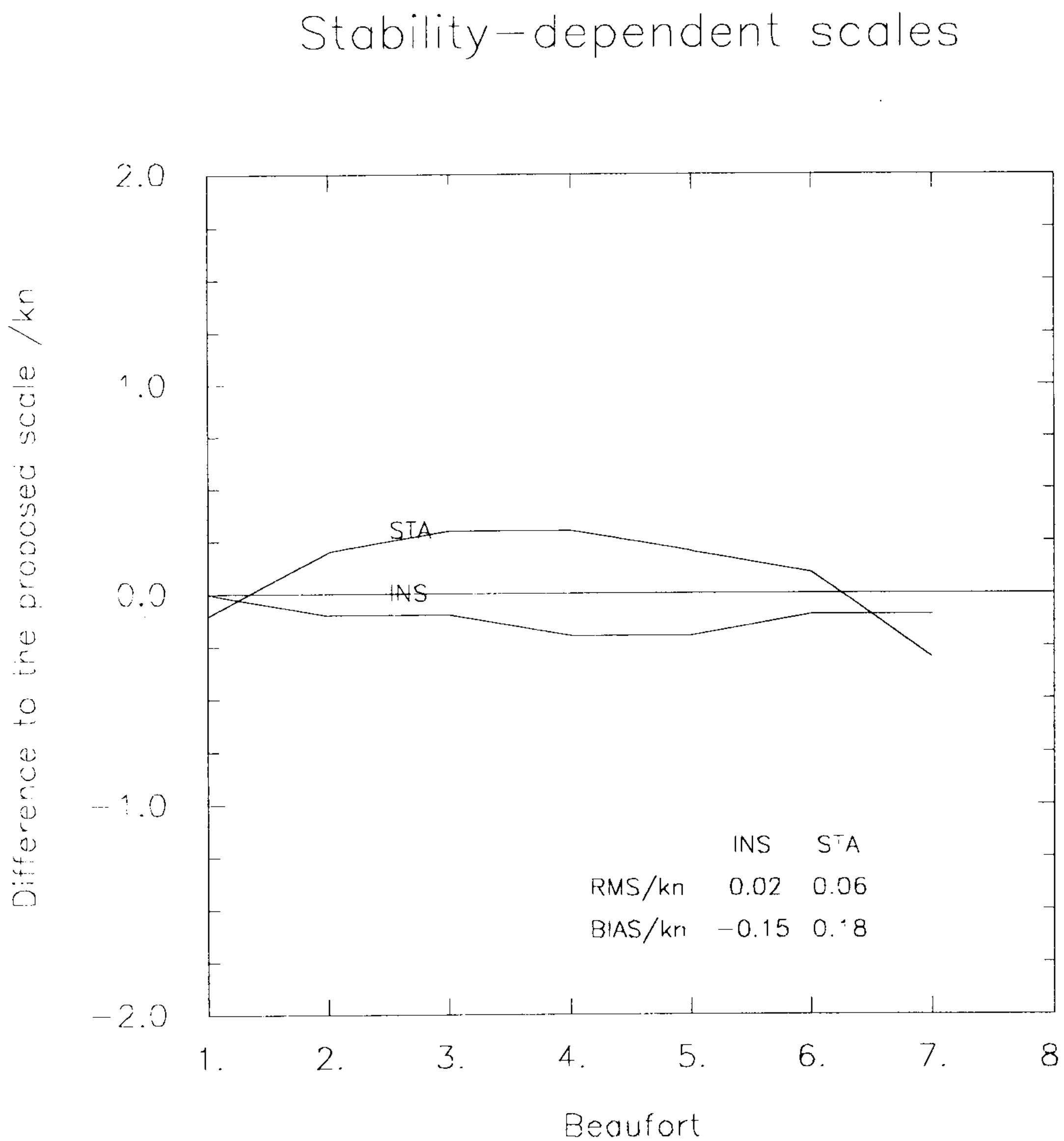

Figure 11: As Fig. 10, but for the USA and Germany, respectively.