# Effects on Wind Statistics and Climatological Air-Sea Flux Estimates in the North Atlantic Ocean

Hans-Jörg Isemer and Lutz Hasse
Institut für Meereskunde
Düsternbrooker Weg 20, D 2300 Kiel 1, Germany

## Abstract

The Beaufort equivalent scale of the World Meteorological Organisation (WMO), used for decades to transform marine Beaufort estimates to surface wind speeds over the oceans, contains systematic errors that depend nonlinearly on the wind speed. Applying a revised scientific equivalent scale instead of the WMO scale produces significant changes in statistics of surface wind speed U over the ocean and, consequently, in all air-sea fluxes that are related to U.

This study quantifies these biases for the North Atlantic ocean. The WMO scale underestimates climatological monthly means of U significantly in most regions, and overestimates local standard deviations of U. Also the annual variation of U is overestimated especially in extratropical latitudes.

Most existing regional and global air-sea flux compilations (including COADS) have been derived using the WMO scale. Hence, large biases are included in these compilations, although they can be partially hidden by an artificial increase of parameterization coefficients. The wind statistics revised according to a more accurate scientific scale allow the application of bulk coefficients in accordance with newer experimental results from the open ocean. Therefore means and statistics of wind speed and climatological estimates of air-sea fluxes over the World Ocean need revision.

## 1. Introduction

The classical method for obtaining wind estimates at the surface over the ocean is to process ship observations of the Voluntary Observing Fleet (VOF). It is only in approximately the last twenty years that a significant fraction of wind reports from VOF ships has been based on anemometer measurements. The majority of reports has been based on wind estimates. Unfortunately, observational methods onboard changed drastically during the period within which observations are available from the open ocean. During this century, estimates have been made subjectively by observers according to the state of the sea surface. Since World War II, the Beaufort-estimated winds have been directly reported (either in knots or $ms^{-1}$) according to the Beaufort equivalent scale. The latter relates Beaufort numbers (which refer to certain characteristics of the sea state) to wind speed expressed in physical units.

Existing climatological air-sea interaction studies use wind speed statistics converted from ship observations by means of the official Beaufort equivalent scale of World Meteorological Organisation (WMO), code 1100 (see e.g. WMO, 1970). Also wind statistics in the COADS are based on this scale (COADS, 1985). This particular scale has been adopted by WMO for operational use in all national weather services. However, even WMO (1970) urgently recommended a revised scientific Beaufort scale (the so-called CMM-IV scale) rather than code 1100 for scientific studies. Among others, Cardone (1969) and Kaufeld (1981) proposed revised equivalent scales which differ considerably from the WMO scale (table 1).

In this study, the biases introduced by the use of the WMO scale are isolated and quantified. This study is part of a project concerning long-term averaged monthly air-sea interaction fields of the North Atlantic Ocean, and is based on a data set which was originally prepared by the late A.F.Bunker (Bunker, 1976). A detailed comparison of the parameterization schemes used by Bunker with observational evidence from the open ocean obtained within the last fifteen years led to a set of revised parameterizations (Isemer et al., 1989). One constituent of the revision is the application of the revised scientific equivalent scale derived by Kaufeld (1981). Here we compare the results of the revised parameterizations, published in detail in Isemer and Hasse (1987) with results of a parallel calculation where the WMO scale is used instead of Kaufeld's scientific scale.

## 2. The Scientific Equivalent Scale of Kaufeld (1981)

For our North Atlantic Ocean study we preferred the scientific equivalent scale suggested by Kaufeld (1981) instead of the CMM-IV scale or Cardone's scale for the following reasons: (1) Kaufeld's data set used for calibration consists of 55000 simultaneous pairs of estimates and measurements. This data set is about ten times as large as that used by Cardone and is therefore statistically more reliable. (2) It stems from nearly the same period and the same region as the Bunker data set. (3) The reference height of 25 m above sea level is known more accurately than that of the CMM-IV scale. (4) Kaufeld used two different statistical methods leading to the same equivalent scale. (5) Kaufeld also checked for regional differences but could not find significant differences in equivalent wind speeds derived from data of single Ocean Weather Ships. We conclude that there is no important difference in observing techniques between observers in different climate regions. Hence, Kaufeld's scale can be applied to wind estimates of the whole North Atlantic Ocean for the post-World War II period.

Comparison of Kaufeld's scale with the official WMO scale (table 1) shows the latter to give lower wind speeds below Beaufort 8 and higher above. Systematic differences for single Beaufort numbers exceed 2 $ms^{-1}$ at Beaufort 3. The wind speed equivalents proposed by Kaufeld (1981) are CMM-IV scale. Note, however, that the difference in reference level has to be properly taken into account when comparing effects and results of different scales.

## 3. The Data Base and Methods Used

*a) The BUNKER Data Set*

The Bunker data set for the North Atlantic Ocean south of 650N contains data for the period 1941 to 1972 (Bunker, 1976, Isemer and Hasse, 1985). More than 90% of the wind reports in this data set were estimated from the sea state. For the transformation to wind speeds the WMO scale, code 1100, was used (Goldsmith and Bunker, 1979). We assume that the possible presence of less than 10% of measurements will not influence the long term average wind speeds significantly. Hence, the wind speed statistics from the Bunker data set are believed to be solely based on wind speed estimates deduced by means of the official WMO scale.

*b) Application of KAUFELD's Equivalent Scale to the BUNKER Data Set*

The difference between wind speeds decoded by the WMO scale, $U_w$, and those decoded by KAUFELD's scale, $U_k$, may be expressed in terms of a correction factor k as a function of $U_w$.

$$U_k = U_w k(U_w) \tag{1}$$

A fit to the ratios of the different equivalent wind speeds (table 1) leads to (see Fig. 1)

$$\begin{aligned} k(U_w) &= (U_w/32)^{-0.3} \qquad for \qquad U_w \le 40kn \\ (k(U_w) &= 0.94) \qquad for \qquad U_w > 40kn \end{aligned} \tag{2}$$

Note, that (2) may only be applied to individual estimates. Individual wind speed values below 32 kn (about Bft. 7) increase, higher values of $\overline{U}_w$ decrease. This will result in a compression of the distribution. The net effect on the average wind speed $\overline{U}_w$ depends on the shape of the distribution: the net increase of $\overline{U}_w$ will be largest in regions were most of the individual observations are below Bft. 7 with $k(U_w) > 1.0$.

As $k(U_w)$ depends nonlinearly on $U_w$ it may not be applied to the average wind speeds of the Bunker data set. Instead, we fit a Weibull distribution (e.g. Justus et al., 1978) to each monthly pair of mean and standard deviation of $U_w$ from the Bunker data set. Relative frequencies $R_i$ for each Beaufort number i are obtained with upper and lower bounds according to the WMO scale. The $R_i$ are attached to the equivalent wind speeds $U_{ki}$ of the scientific scale, thus modifying the distribution in terms of wind speed. Now, new means $\overline{U}_k$ and standard deviations $\sigma_k$ are calculated from the modified distributions. Hence, we have available long-term averaged monthly fields of $\overline{U}_k$ and $\sigma_k$ for the North Atlantic Ocean, which may be seen as decoded by means of the scientific scale of Kaufeld.

These climatological averages of wind speed are defined for a nominal reference level of 25 m height. In order to facilitate comparison with the WMO scale statistics, we reduce wind speeds derived from the scientific scale to 10m nominal height above sea level using the logarithmic wind profile.

## 4. Results

*a) Wind Speed*

In the North Atlantic Ocean extreme monthly means $\overline{U}_k$ and $\sigma_k$, and also the most pronounced regional variability of $\Delta U$, are found in January (Fig. 2). Values of $\overline{U}_k$ are in general higher than those of $\overline{U}_w$. In January, differences $\Delta\overline{U} = \overline{U}_k - \overline{U}_w$ are smallest in the west wind drift and increase with decreasing latitude. Even small negative values occur south of Greenland, while $\Delta U$ exceeds 1.5 $ms^{-1}$ in the tropics. In general, the 0.6 $ms^{-1}$ isoline separates significant from insignificant differences (according to the $x^2$-test with 1% error level) to a good approximation. In summer, regional differences of $\Delta\overline{U}$ are smaller: typical values are 1.3ms$^{-1}$ in the subpolar regions and between 1.3 and 1.7 ms$^{-1}$ near the equator. Differences are significant everywhere in the North Atlantic Ocean. Inspection of all monthly maps indicates that $\Delta\overline{U}$ is significant except in the westerlies from mid-autumn to mid- spring.

There is a distinct annual variation in $\overline{U}_k - \overline{U}_w$ depending on latitude (Fig. 3): the amplitude in the annual cycle of $\Delta\overline{U}$ is highest at about 60°N and decreases with decreasing latitude. South of about 25°N almost no annual cycle of the wind speed difference is detectable. This leads to a characteristic difference in the annual variation of $\overline{U}_k$ versus $\overline{U}_w$. While the difference of the annual variation is less than 0.5 ms$^{-1}$ in the tropics, the use of Kaufeld's scale leads to substantially decreased annual variations of wind speed of more than 1.5 ms$^{-1}$ in the westerlies.

To sum up, the bias in climatological wind speed is lowest for wind speed samples with high first and second moments (typical for winter scenarios in subpolar latitudes). The bias is high, if first and/or second moments of the sample are small (e.g. trade wind or near-equatorial regions). These particular regional and seasonal characteristics of monthly wind speed biases lead to an overestimate of the annual variation of wind speed, especially in extra-tropical regions.

*b) Standard Deviations of Wind Speed*

$\sigma_k$ increases with latitude from less than 2 ms$^{-1}$ in the tropics to more than 6 ms$^{-1}$ (4 ms$^{-1}$) in the westerlies in winter (in summer), indicating higher variability of wind speed in the regions with frequent cyclone and storm activities (Fig. 4). In monthly maps the range of $\sigma_k$ is even higher: values between 1.5 ms$^{-1}$ (in the core region of the trade winds) and 7.3 ms$^{-1}$ (south of Greenland) mark the evident differences between characteristic climate regions in the North Atlantic Ocean. The change of standard deviation $\Delta\sigma = \sigma_k = \sigma_w$ is negative everywhere in the North Atlantic Ocean except the near equator region in winter and spring (Fig. 4). In general, A$\sigma$ decreases with increasing latitude.

*c) Mean Wind Direction and Directional Steadiness*

Based on 420 real monthly wind samples from different wind climates in the Atlantic Ocean no significant difference was found in either the mean monthly wind direction or the directional steadiness of the wind when applying the scientific instead of the WMO scale. While the change in direction is in general less than 3° and reaches 5° in very few samples the steadiness is not changed by more than 5%. However, the mean annual wind direction may be changed remarkably (see Böning et al., 1991).

*d) Latent Heat Flux and Evaporation*

In the west wind drift, zonal averages $\Delta Q_L = Q_{Lk} - Q_{Lw}$ (Fig. 5) caused by the use of Kaufeld's equivalent scale are between -6 Wm$^{-2}$ (5% of $Q_{Lk}$ in December/January) and -12 Wm$^{-2}$ (> 25% in July to September). Here, differences are small throughout the year because in winter, with high fluxes, $\Delta\overline{U}$ is small while in summer, when $\Delta\overline{U}$ increases, $Q_L$ is small. South of 40°N differences exceed -20 Wm$^{-2}$ everywhere in the North Atlantic Ocean, are less than -30 Wm$^{-2}$ (≈ 20%) in the trades in summer, and reach -40 Wm$^{-2}$ (≈ 25) in winter. The percentages mentioned are in general also valid for the differences occurring in the monthly maps while the absolute differences are even higher. The latter exceed 50 $Wm^{-2}$ in winter in the subtropics. The resulting differences in zonal averages of evaporation rates vary between 0.8 cm/month and 4.3 cm/month. The total annual average of the North Atlantic Ocean difference of $Q_L$ is -24 $Wm^{-2}$ equivalent to about 0.3 m of evaporated water per year or about $1.3*10^{13}$ tons of water. This is a remarkable bias in the hydrological cycle (of order 20%), caused by using the wrong Beaufort equivalent scale.

*e) Net Air-Sea Heat Flux*

Differences in climatological estimates of sensible heat flux $Q_H$ caused by application of the revised Beaufort scale sum up with those in $Q_L$ just presented giving the difference in net air-sea heat flux Q. As the average Bowen ratio in the North Atlantic Ocean is about 0.15, zonal averaged differences $\Delta Q = Q_k - Q_w$ increase by only -1 to -5 $Wm^{-2}$ compared to $\Delta Q_L$ showing very similar patterns to those of $\Delta Q_L$.

Zonal annual averages of AQ are between -9 $Wm^{-2}$ at 55°N and -45 $Wm^{-2}$ at 18°N (Fig. 6a) with a North Atlantic Ocean average of -27 $Wm^{-2}$. The oceanic meridional heat transport H may be calculated by integrating Q starting at 65°N and proceeding southward (Fig. 6b). Differences in H, caused solely by using the wrong Beaufort scale, reach 0.4 PW (1 PW = $10^{15}$W) at 25°N and 1.15 PW at the equator. The difference at the equator is larger than the estimate of IH87 itself. Using the WMO scale instead of Kaufeld's scale but retaining all other data and parameterization techniques would result in an unrealistic southward-directed trans-equatorial heat transport of -0.45 PW.

*f) Wind Stress*

Since the wind stress $\vec{\tau}$ at the ocean surface depends on the square of the wind speed, differences caused by the two Beaufort scales are even more pronounced (Fig. 7). While in subpolar regions $\Delta\tau$ is moderate (between 1 and $2*10^{-2}$ $Nm^{-2}$), it exceeds $4.5*10^{-2}$ $Nm^{-2}$ in the trade wind region in winter. The latter value is more than 30% of the revised wind stress results (or more than 50% based on the results with the old wind statistics). Integrating the curl of wind stress, the Sverdrup balance in the North Atlantic Ocean is computed with both wind statistics but equal parameterization techniques. While with the revised wind statistics, 35 Sv (1 Sv = $10^6 m^3 s^{-1}$) is obtained across 31°N, application of the old wind statistics only yields 23 Sv, a drastic underestimate of about 30%.

## 5. Summary and Conclusions

Users of marine meteorological data compilations should be aware of the facts that (i) different equivalent scales used may lead to significant different wind statistics, and that (ii) surface wind statistics available from existing compilations are based on the official Beaufort equivalent scale of WMO. The latter scale contains systematic errors, which lead to a significant underestimate of climatological mean wind speeds, and to a significant overestimate of standard deviations of wind speed. We emphasize that also wind estimates in the COADS are based on the WMO scale.

Estimates of evaporation, oceanic surface heat loss, wind stress, and other air-sea exchange quantities related to surface wind, are considerably underestimated by the WMO scale. Implications on estimates of e.g. the hydrological cycle, ocean fresh water fluxes, and ocean heat transports on a regional and global scale are evident. The bias depends on season, and it varies regionally. Hence, the amplitude of the annual cycle of air-sea fluxes is affected as well in a regional varying way. As the coupling between ocean and atmosphere is mainly due to wind stress and energy transfer, the use of the biased equivalent scale has a remarkable effect on estimates of the forcing of oceanic motion.

We recommend the scientific scale deduced by Kaufeld (1981) which is similar to both the CMM-IV scale and that proposed by Cardone (1969, see also Cardone et al., 1990). However, even small differences in equivalent scales may lead to substantial differences in wind statistics (Da Silva et al., 1992). The scale derived by Kaufeld is based on a much larger data set than Cardone's scale. Reference height, data sets used, and calibration procedures are more precisely documented than for the CMM-IV scale.

Most existing air-sea flux climatologies probably contain two major systematic errors with regionally and seasonally varying characteristics: underestimated mean wind speeds are compensated, but insufficiently and only in part, by artificially increased bulk coefficients. Using the recommended scientific scale allows the application of bulk coefficients in accordance with newer experimental results from the open ocean (Isemer and Hasse, 1987, henceforth IH87). Recently, Böning et al. (1991) compared in detail the wind stress climatology of IH87 versus that of Hellermann and Rosenstein (1983) using both as atmospheric forcing to an eddy-resolving numerical model of the North Atlantic Ocean. One remarkable result is that the transport of the Florida Current predicted by the numerical model is in much better agreement with direct observations when the North Atlantic is forced by the IH87 climatology. This agreement of the transport concerns both the annual mean and the amplitude of the seasonal cycle.

We recommend revision of existing marine wind statistics and air-sea flux estimates. An ad-hoc approach would require the first and second moments of wind speed samples as suggested in this paper (for more details see Isemer and Hasse, 1991). However, this method is not applicable if a significant fraction of measurements is included. Knowing the percentage of measurements included the approach of Cardone et al.(1990) seems to be especially useful. However, even the COADS products (at least the "monthly summary trimmed groups") do not contain this information. Hence, we suggest a re- evaluation of global marine wind statistics based on the individual observations of the post World War II portion of the COADS. This procedure should include also corrections for measurement heights and stability effects as pointed out by Cardone et al.(1990), and, of course, for other biases known so far (see Isemer, 1992). Unless such detailed corrections are performed, in future, wind statistics based on estimates should be separately archived from those based on measurements.

This effort will not solve all heat budget problems, but we emphasize our feeling that an important mean bias will be excluded from present air-sea flux estimates.

## Acknowledgements

This is a contribution of the Sonderforschungsbereich 133 “Warmwassersphäre des Atlantiks” at the Institut für Meereskunde, Kiel, F.R.G. It is a shortened version of a recently published paper (Isemer and Hasse, 1991). We acknowledge the financial support of the Deutsche Forschungsgemeinschaft. Thanks to Frauke Nevoigt for drafting the figures.

## REFERENCES


Böning, C.W., Dösher, R., and Isemer, H.-J., 1990: Monthly mean wind stress and Sverdrup transports in the North Atlantic: A comparison of the Hellermann-Rosenstein and Isemer-Hasse climatologies. *Journal of Physical Oceanographer*, **21**, 221-239

Bunker, A.F., 1976: Computations of surface energy flux and annual air-sea interaction cycles of the North Atlantic Ocean. *Monthly Weather Review*, **104**, 1122-1140

Cardone, V.J., 1969: Specification of the wind distribution in the marine boundary layer for wave forecasting. *Report TR69-1*, New York University, New York, NY, 131 pp

Cardone, V.J., Greenwood, J.G. and Cane, M.A., 1990: On trends in historical marine wind data. *Journal of Climate*, **3**, 113-127

COADS, 1985: *Comprehensive Ocean-Atmosphere Data Set, Release 1.*, edited by R.J. Slutz et al. Climate Research Program, ERL, Boulder, Colorado, USA.

Da Silva, A.M., Young, C.C. and Levitus, S., 1992: A note on the effect of scientific Beaufort scales on climatological wind statistics. Unpublished manuscript, presented in part at the COADS meeting 1992.

Goldsmith, R. and Bunker, A.F., 1979: WHOI collections of climatology and air-sea interaction data. *Technical Rep., WHOI-79-70*, Woods Hole Ocean.Institute, Woods Hole, Mass.

Hellerman, S. and Rosenstein, M., 1983: Normal monthly wind stress over the World Ocean with error estimates. *Journal of Physical Oceanographer*, **13**, 1093-1104

Isemer, H.-J., 1992: Comparison of estimated and measured marine surface wind speeds. presented at the COADS user meeting, Boulder, Colorado, January 1992, see this volume.

Isemer, H.-J. and Hasse, L., 1985: *The BUNKER climate atlas of the North Atlantic Ocean*. Volume 1: Observations. Springer Verlag, Heidelberg, New York, Tokyo, 218 pp

Isemer, H.-J. and Hasse, L., 1987*: *The BUNKER climate atlas of the North Atlantic Ocean. Volume 2*: Air-sea interactions. Springer Verlag, Heidelberg, New York, Tokyo, 252 pp

Isemer, H.-J., Willebrand, J. and Hasse, L., 1989: Fine adjustment of large scale air-sea energy flux parameterisations by direct estimates of ocean heat transport. J.Climate, 2, 1173-1184

Isemer, H.-J. and Hasse, L., 1991: The Scientific Beaufort Equivalent Scale: Effects on wind statistics and climatological air-sea flux estimates in the North Atlantic Ocean. *Journal of Climate*, **4**, 819-836

Justus, C.G., Hargraves, W.R., Mikhail, A. and Graber, D., 1978: Methods for estimating wind speed frequency distributions. *Journal of Applied Meteorology*, **17**, 350-353

Kaufeld, L., 1981: The development of a new Beaufort equivalent scale. *Meteorologische Rundschau*, **34**, 17-23

World Meteorological Organization (WMO), 1970: Reports on marine science affairs. *Rep. No. 3: The Beaufort scale of wind force*. WMO, Geneva, Switzerland, 22 pp

Table 1. Comparison of equivalent wind speeds and intervals of different Beaufort equivalent scales. Note, that slight differences occur in different sources, especially for the WMO equivalents.

I: Scientific scale derived by Kaufeld (1981),

II: WMO scale, code 1100, taken from WMO (1970),

III: Scientific scale proposed by the Commission of Maritime Meteorology of WMO (CMM-IV scale), taken from WMO (1970),

IV :Scientific scale derived by Cardone (1969), converted to knots. Units are knots.

| Bft. number | Equivalent wind speeds I | II | III | IV |
|---|---|---|---|---|
| 0 | 0.7 | 0.0 | 1.6 | - |
| 1 | 3.7 | 1.6 | 3.9 | 3.7 |
| 2 | 8.0 | 4.7 | 7.0 | 7.6 |
| 3 | 12.4 | 8.4 | 10.9 | 11.5 |
| 4 | 16.9 | 13.0 | 15.2+ | 15.6 |
| 5 | 21.4 | 18.3 | 19.8 | 19.6 |
| 6 | 26.0 | 23.9 | 24.5 | 23.9 |
| 7 | 31.0 | 30.1 | 29.4 | 28.3 |
| 8 | 36.3 | 36.7 | 34.6 | 33.3 |
| 9 | 42.3 | 43.9 | 40.4 | 39.8 |
| 10 | 48.7 | 51.3 | 47.0 | 46.5 |
| 11 | 55.6 | 59.3 | 54.4 | 50.7 |
| 12 | 63.0 | 67.7* | 62.6 | 53.7 |

* from Kaufeld (1981)

+ see WMO (1970, page 17), the value of 7.9 $ms^{-1}$ on page 19 is a misprint (Kaufeld, personal communication).

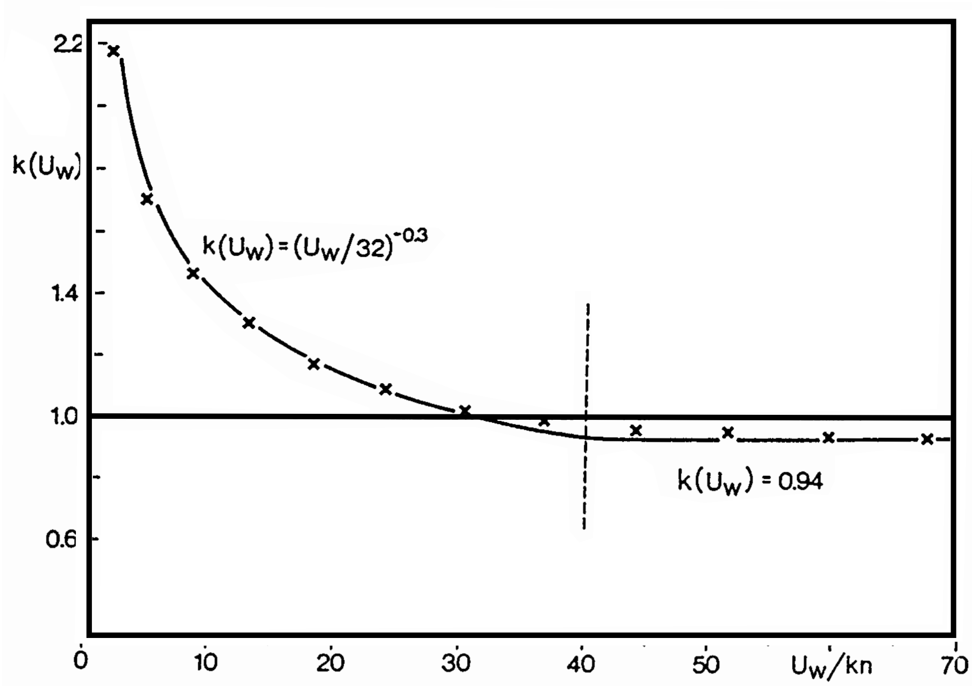


Figure 1. The correction function $k(U_w)$ as a function of wind speed $U_w$ decoded by the WMO equivalent scale. Crosses denote the conversion from the WMO scale to the scientific scale of Kaufeld (1981) based on the equivalent wind speeds (Table 1). The curve represents the best fit to the equivalent wind speed ratios (redrawn from isemer and Hasse, 1987).

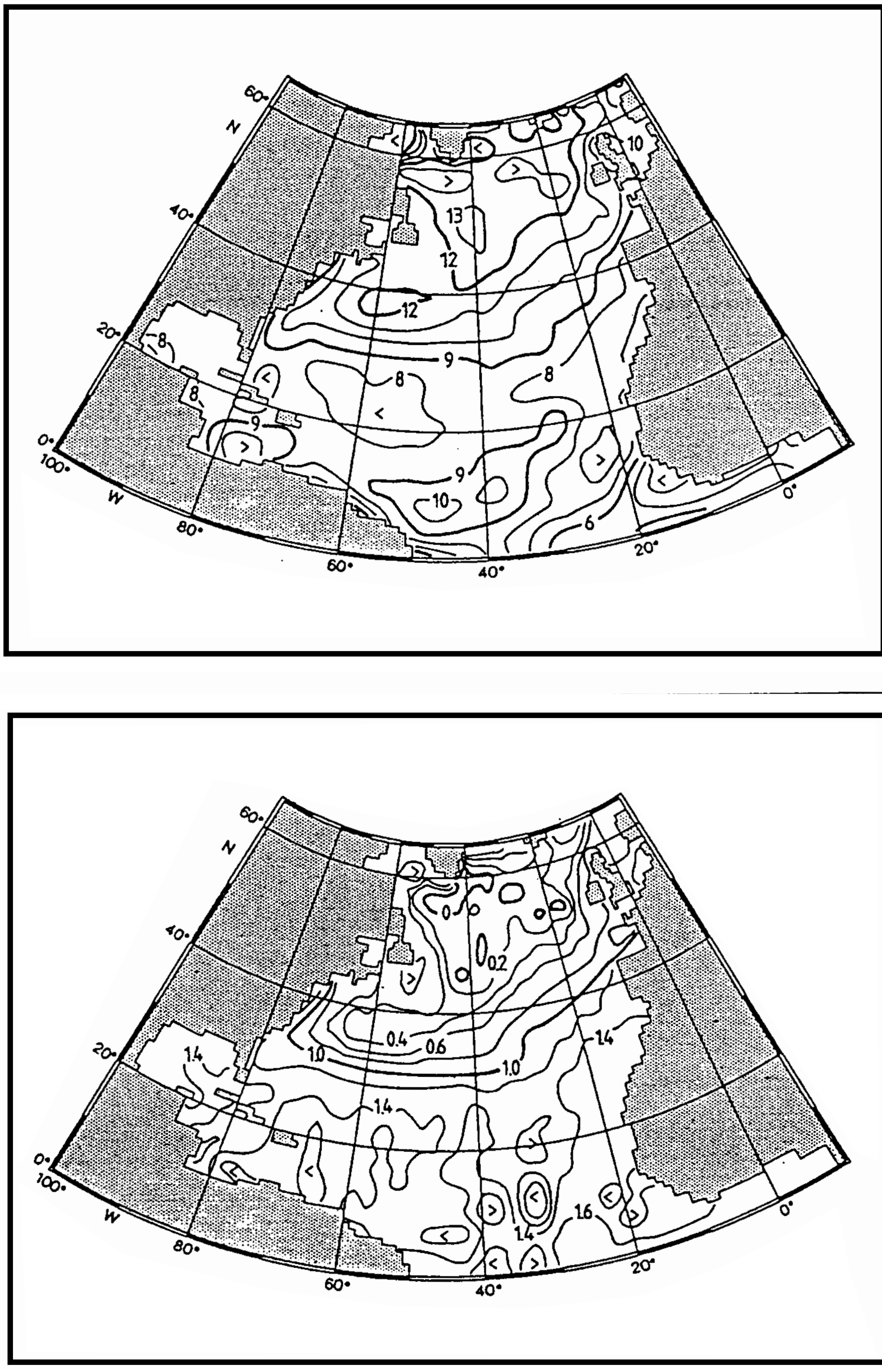


Figure 2. Top: mean January wind speed $\overline{U}_k$ ($ms^{-1}$) at the surface of the North Atlantic Ocean using Kaufeld's (1981) equivalent scale for decoding ships' wind estimates. Bottom: Difference $\overline{U}_k$ - $\overline{U}_w$ ($ms^{-1}$) for January showing the effect of using Kaufeld's scale instead of the WMO scale. The nominal reference height is 10 m above sea level.

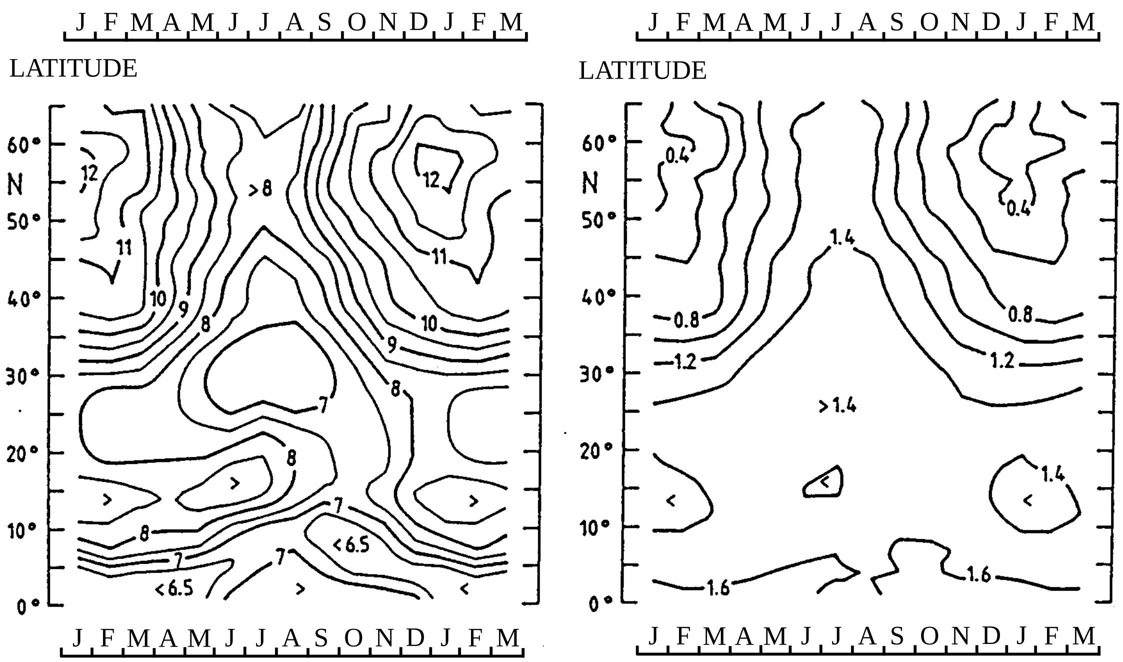


Figure 3. Zonally averaged monthly wind speed $\overline{U}_k$ (left) and wind speed differences $\overline{U}_k$ - $\overline{U}_w$ (right) as a function of latitude and time of year in the North Atlantic Ocean. Units are $ms^{-1}$. The nominal reference height is 10 m above sea level.

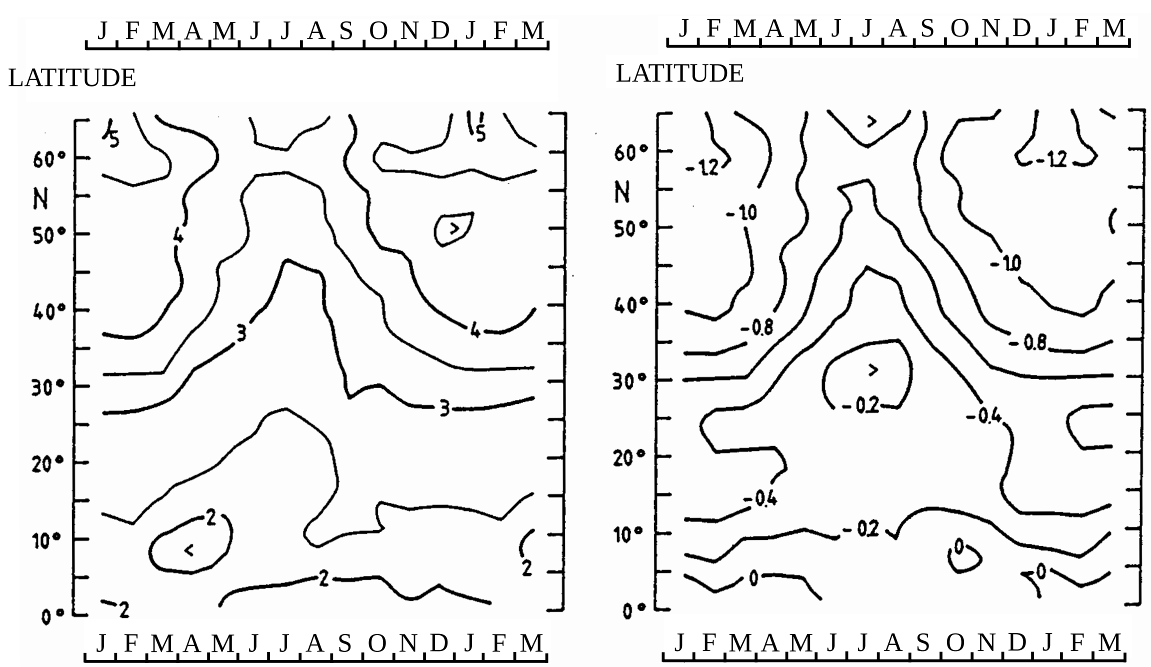


Figure 4. As in Figure 3, but showing monthly local standard deviations $\sigma_k$ (left) and the difference $\sigma_k$ - $\sigma_w$ (right).

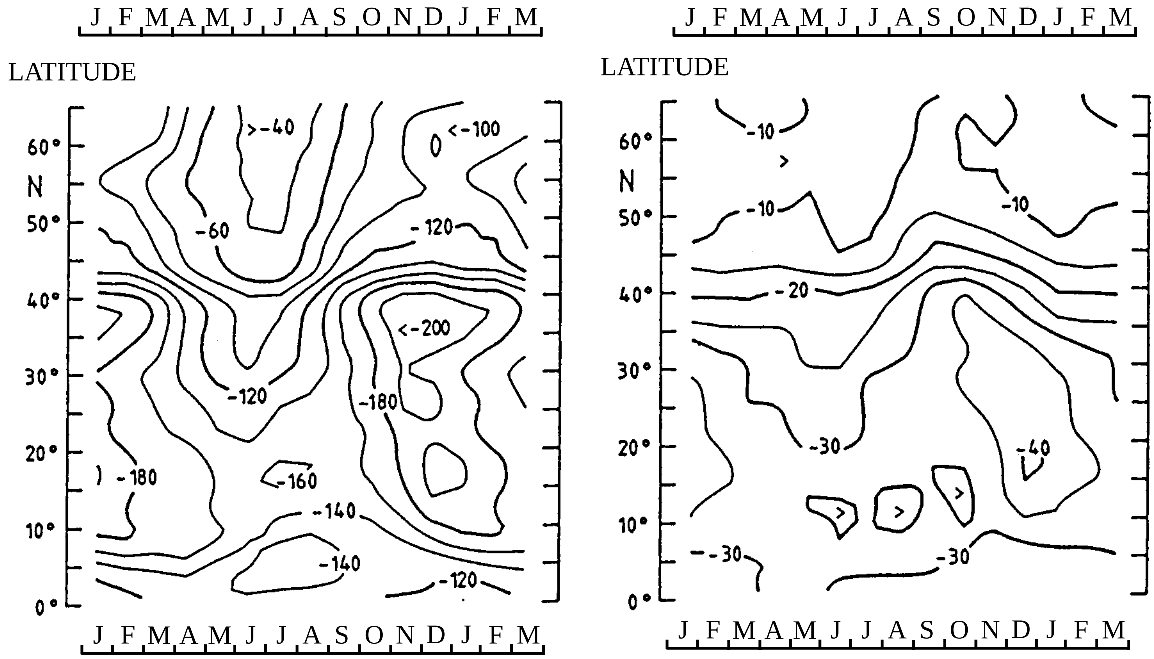


Figure 5. Left: Zonally averaged monthly latent heat flux $Q_{LK}$ ($Wm^{-2}$) as a function of latitude and time of year at the surface of the North Atlantic Ocean (taken from Isemer and Hasse, 1987). Negative sign denotes upward flux. Kaufeld's revised scale is used for decoding ships' wind estimates. Right: $Q_{LK}$ - $Q_{LW}$ ($Wm^{-2}$), showing the effect of the use of Kaufeld's scale instead of the SMO scale. The negative sign indicates higher upward fluxes with $Q_{LK}$.

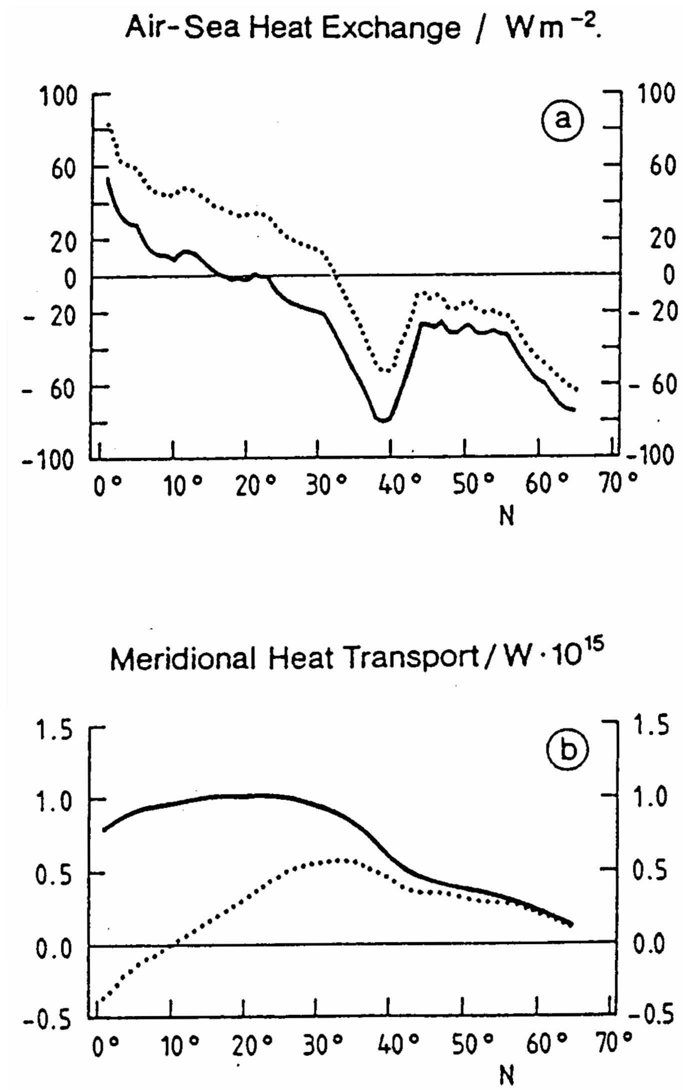


Figure 6. a) Zonal averages of annual net air-sea heat exchange ($Wm^{-2}$) as a function of latitude in the North Atlantic Ocean and b) meridional oceanic heat transport (PW, 1PW = $10^{15}$W) computed from the former. Positive values indicate downward flux and northward transport, respectively. Solid line: Using Kaufeld's scale for decoding ships' wind estimates (from Isemer and Hasse, 1987). Dotted line: Using the biased WMO scale instead.

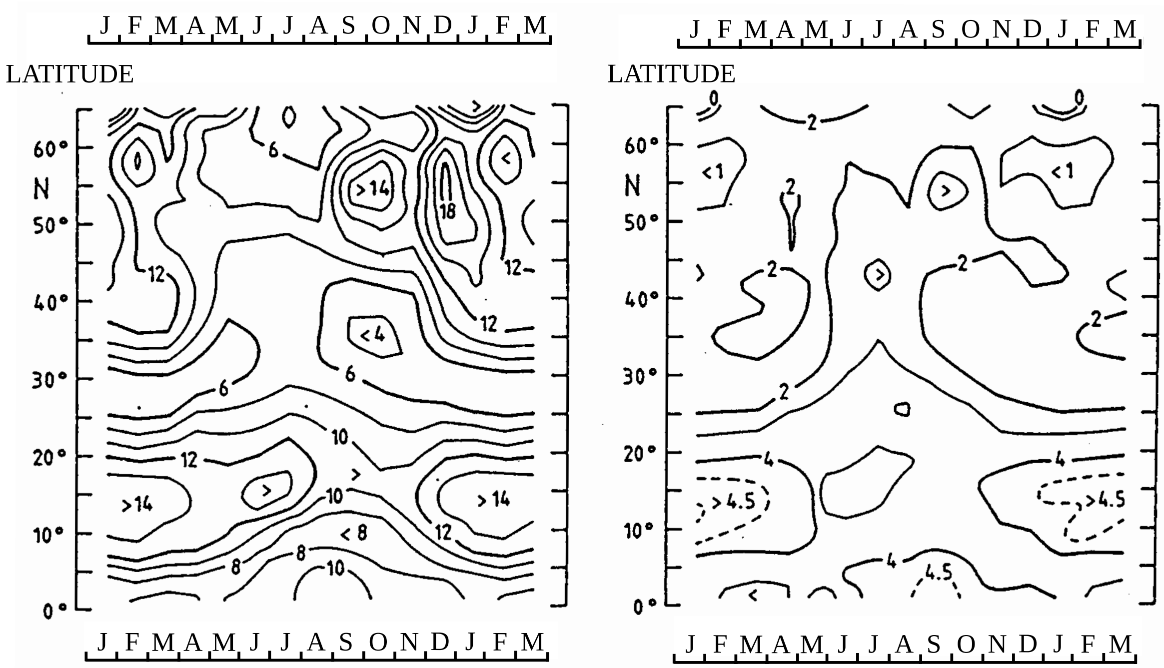


Figure 7. As in Figure 5, but showing the magnitude of the surface wind stress vector $|\vec{\tau}|$ (left), and the effect of the biased WMO scale on $|\vec{\tau}|$ (right). Units are $10^{-2}$ $Nm^{-2}$.