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# A COMPARATIVE STUDY OF OBSERVED AND GCM-SIMULATED TURBULENT SURFACE FLUXES AT THE POSITIONS OF ATLANTIC WEATHERSHIPS

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ABSTRACT

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If oceanic models are to be driven with transient atmospheric input, data from standard daily analyses or from an atmospheric GCM simulation can be used. The question arises whether these "FF-data" (FF = field forcing) are appropriate to be used as a realistic oceanic forcing in the form of wind stress and turbulent heat fluxes.

A series of different FF-data sets is compared with respective "LF-data" (LF = local forcing) derived from in situ weathership observations. We believe these LF data to be the most accurate and reliable long year maritime time series. The study is restricted to 8 Atlantic weatherships and January conditions and to fields obtained with the Hamburg University GCM or derived from analyses of the German Weather Service (DWD).

It turns out that DWD based FF data sets are suitable only if long year mean values are required. In general, the interannual and synoptic scale variability is too small for all FF data sets. With respect to the windstress, the empirical formulae to obtain the surface wind (from the sea level pressure field) together with the usage of a windspeed dependent drag coefficient yield the best though still unsatisfying results. The approach using generalized similarity theory gives worse results with respect to the synoptic scale and interannual variability.

The GCM simulated data set is systematically biased over wide regions which is partly due to a shift in the model's quasistationary Icelandic Low and an increased temperature at the model's lowest level. The transients are simulated at some positions even poorer than those analysed by the DWD, but at other positions superior though still weaker than the LF data's.

## 1. INTRODUCTION

The knowledge of the horizontal distribution of the vertical turbulent exchange of momentum and energy at the atmosphere–ocean interface is important for studies of oceanic currents, of the heat content of the oceanic mixed layer as well as for studies of the general circulation of the atmosphere. The significance of this was strengthened recently by the Scientific

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Steering Group of the Tropical Ocean/Global Atmosphere (TOGA) Programme (WCRP, 1983) and by the workshop on Interim Ocean Surface Wind Data Sets (WCRP, 1984).

Generally in the past, long year means of monthly mean fluxes have been calculated (e.g., by Houghton (1954), Budyko (1963), Hellermann (1965), Bunker (1976) and Han (1983)) and adopted for ocean circulation studies. These long year means are no longer suitable if, for example, the effect of migrating synoptic scale patterns with time scales of days or several weeks (forecast studies, e.g., Fischer (1979), as well as climate studies) or the variability of the ocean currents or of the coupled system atmosphere/ocean is to be investigated. (Of course, the problem is the same for sea ice problems at time scales of days and several weeks, but no time series of in-situ observations at fixed sea ice positions of sufficient length are available to us.)

For such studies, a transient atmospheric input covering regularly and (more or less) finely the area of concern is necessary. Since available maritime in-situ observations generally do not fulfil this coverage-condition the input has to be taken either from standard regular (e.g., daily or 12-hourly) operational analyses of the weather services or from an atmospheric GCM. The stresses (and energy fluxes) are then parametrized from gridded synoptic scale variables, first of all from the surface pressure field. This forcing is denoted as "FF" (= field forcing) in the following.

Problems related to FF-data derived from analyses are:

(1) owing to the sparse observations over the ocean, the resolution of the pressure field is generally poor. Furthermore, to suppress spurious noise, the original pressure fields are filtered, which leaves the synoptic scales affected. Therefore, one can expect synoptic scale disturbances to be too smoothed, even though they become corrected with the latest forecast. A comparison by Bruening (1982) between DWD objective surface pressure analyses and handmade analyses by Seewetteramt Hamburg regarding some storm cyclones in the North Sea area gave underestimations of the pressure in the cyclone's centre up to 13 mbar by the objective analyses corresponding to a geostrophic wind difference of $\sim 30 \text{ m s}^{-1}$;

(2) mesoscale vortices which are connected with geostrophic winds up to and $> 100 \text{ m s}^{-1}$, are often badly resolved by the analyses. An example observed in the North Sea exhibits a discrepancy between the geostrophic wind based on standard analyses and a mesoscale analysis of $> 50 \text{ m s}^{-1}$ (Paulus, 1983); and

(3) the abrupt changes of the turbulent fluxes connected with the poorly resolved small scale fronts are insufficiently described by the analyses.

In the case of a GCM, it is not necessary to analyse the atmosphere's state by means of irregularly distributed observations with limited reliability.

However, owing to the limited horizontal (here: ~ 300 km) and vertical (~ 300 mbar) resolution, subgrid-scale processes, as mesoscale vortices and fronts, are not simulated. Furthermore, the climate established by a GCM is not identical with the observed climate (e.g., von Storch and Roeckner, 1983). One has to expect the location and intensity of, for example, the quasistationary features to be different from the observed ones. This will of course influence the quality of the atmospheric forcing at the ocean's surface.

The objective of this paper is to evaluate how realistic a FF-forcing (based on DWD analyses or on simulations performed with the Hamburg University GCM) is. Thus, it is related closely to the TOGA Programme (WCRP, 1983). An objective comparison of the FF data with respective "LF-data" sets, i.e., with data based on in-situ observations is performed (cf. WCRP, 1984). Since a sufficiently long time series of maritime in-situ observations are available only for the oceanic weatherships, we restrict ourselves to the 8 positions of the Northern Atlantic weatherships A–E and I–K, which are sketched in Fig. 1. Furthermore, only January data are considered.

The different methods (FF; LF) to obtain the fluxes are outlined in

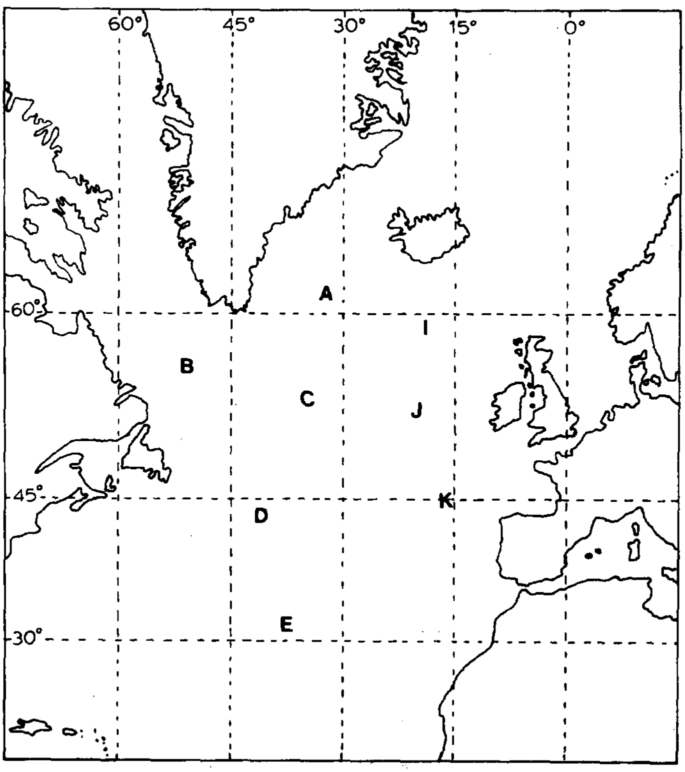



Fig. 1. Position of the 8 Atlantic weatherships, from which data are investigated in this study.

section 2. As the timeperiods for the different data sets (in-situ observations: 1950–70; DWD analyses: 1967–83; GCM data: 9 simulated Januaries) do not coincide, statistical ensemble-comparison techniques are used; see section 3. In section 4 the results are discussed in terms of monthly means and monthly autospectra.

## 2. THE DATA

Turbulent surface fluxes of momentum ($\tau$, units: Pa) and of latent and sensible heat ($LE$ and $H$, units $\mathrm{Wm}^{-2}$) are studied.

### *2.1. FF-data (FF = field forcing)*

FF data, i.e., fluxes parameterized from synoptic scale atmospheric flow are obtained from daily DWD analyses of the Januaries 1967–83 and from a perpetual January GCM-run (300 days).

#### *2.1.1. FF-data based on daily DWD analyses*

Three different parameterizations are used: L = Luthardt and Hasse (1983); D = Duun-Christensen (1975); and Y = Yamada (1976). D and L estimate surface winds from the sea level pressure field (SLP):
(L)

$$\left.\begin{aligned} U &= (0.59 - 0.03\Delta T)G + 2.1 + 0.05\Delta T \quad [\mathrm{m\ s^{-1}}] \\ \alpha &= 4.4\Delta T + 14.5 \quad [\mathrm{deg}] \end{aligned}\right\} \quad \text{if } |G| < 20\ \mathrm{m\ s^{-1}}$$

$$\left.\begin{aligned} U &= 0.41G + 5.8 \quad [\mathrm{m\ s^{-1}}] \\ \alpha &= 3.3\Delta T + 4.4 \quad [\mathrm{deg}] \end{aligned}\right\} \quad \text{if } |G| > 20\ \mathrm{m\ s^{-1}}$$

where $G$ denotes the geostrophic windspeed, $\Delta T$ the difference air–sea of potential temperature, $U$ the surface windspeed and $\alpha$ the cross-isobar angle.
(D)

$$U = 6.82\sqrt{(0.54 - 0.012\Delta T)G + 1.68 - 0.105\Delta T} - 11.0 \qquad [\mathrm{m\ s^{-1}}]$$

$$\alpha = 2.8(|\Delta T| + 0.7) + 11.4 \qquad [\mathrm{deg}]$$

From the surface wind $u$ the stress is obtained via the standard bulk formula

$$\tau = \rho C_D U u \qquad (1)$$

where $C_D$ is the drag coefficient and $\rho$ the density of the air.

Thus, the data needed for L and D are SLP, the air–sea temperature difference $\Delta T$ and the density. Unfortunately, the latter two are not included in the regular analyses. Therefore, some apprioriate a priori fixed values have to be assigned to $\Delta T$ and $\rho$. Coinciding with common practice we chose:

$$\rho = 1.2 \text{ kg m}^{-3} \text{ and } \Delta T = -2°\text{C} \quad (2)$$

For the drag coefficient, we applied either

$$C_D = 1.3 \cdot 10^{-3} \quad (3)$$

or

$$C_D = (1.18 + 0.016U) \cdot 10^{-3} \quad (4)$$

Theoretically, at least, the drag coefficient should not depend on the windspeed, but measurements (e.g., Brocks and Kruegermeier, 1970) point to relations as (4) over sea, which may reflect the fact that the surface roughness is increased by enhanced swell. The consideration of the dependency of $C_D$ on the thermal contrast air–sea of, say $-2°$C, would increase the drag coefficient by 1–6%.

As far as I know, no systematic discussion of the respective merits and demerits of D and L has been published yet. The windspeeds derived from both formulae are similar (see fig. 3 of Luthardt and Hasse, 1983). The main differences are: D is a fully empirical formula; L uses a physically plausible linear dependence with empirically fitted constants. The cross isobar angle given by the older scheme D is independent of the sign of the thermal air–sea contrast, while L depends on the sign of $T$. Since I prescribe a fixed value $\Delta T$, the latter advantage of L is unactive in this study.

We use both, (3) and (4), and distinguish the different fluxes by the notations as, for example, "FF L3" (= Field Forcing; Luthardt and Hasse, 1983, $C_D$ according to (3)).

Parameterization Y calculates the momentum fluxes from generalized similarity theory with empirical constants derived by Yamada (1976). For details, see Roeckner (1979). The stresses obtained in this way depend on the vertically averaged boundary layer geostrophic wind and the difference of the virtual potential temperature at the top of the PBL and the sea surface. The geostrophic wind mentioned above is approximated by the mean of the geostrophic wind at the surface and at 850 mbar. Analogous to (4), a surface roughness parameter $z_0$ dependent on the friction velocity is caused.

Unfortunately, the temperature of the atmosphere is mostly unknown for the PBL but only known for 850 mbar, which is frequently above the PBL. To overcome this problem, a correction using an estimated PBL height is inserted.

Since Y takes into account the changes of the bulk stability parameter, one should expect this scheme to be superior to L and D. It will be shown below that this is untrue.

The basic data for the three procedures L, D and Y are:

(1) daily DWD analyses of SLP for the Januaries 1967–83 (for D, L and Y);

(2) daily DWD analyses of temperature and geopotential height at 850 mbar for the same Januaries (for Y); and

(3) the climatological January SST distribution given by Alexander and Mobley (1976) (for Y). (This climatological SST distribution belongs seemingly to the most reliable ones, see Reynolds (1983).)

Thus, FF momentum fluxes based on DWD analyses are available for 17 individual Januaries. These analyses are given originally on an octagon (cartesian) grid. For technical reasons, we used data interpolated onto a regular 2.8°–$\lambda$–$\phi$-grid.

#### *2.1.2. GCM generated FF data*

Daily data produced by the Hamburg University GCM (Roeckner, 1979) are used. Parameterization Y was implemented to obtain surface stresses and sensible heat fluxes $H$ and a similar one with empirical constants derived by Brutsaert and Chang (1978) to calculate the latent heat fluxes. A 300 day run in the perpetual January mode is used, which is subdivided into 10 30-day intervals. Each of these 10 intervals is regarded as one GCM-generated January. In the first January, the model reached its quasistationary state. Thus, only the last 9 Januaries are considered. A discussion and a comparison with observations in terms of meridionally and zonally averaged geopotential height of the 300 day run is given by Von Storch and Roeckner (1983). In the following, this data set is denoted by "FF GCM".

### *2.2. LF-data (LF = local forcing)*

"LF-data" are data derived from in-situ observations: standard bulk formulae with transfer coefficients dependent on the static stability after Kondo (1975) using wind, temperature and dew point at 10m and SST at the location of the respective weathership are used. Esbensen and Reynolds (1981) found Kondo's coefficients to coincide sufficiently with the quite advanced ones given by Liu et al. (1979). The observations cover the Januaries 1950–70. The calculation itself was done by Assmann (1983), who got the meteorological raw data from Seewetteramt Hamburg.

## 3. CONSIDERED QUANTITIES AND METHOD OF COMPARISON

The considered quantities are:

(1) monthly means of the fluxes $\tau$, $H$ and $LE$, the latter two are available only for LF and FF–GCM. These means are computed with the "sampling

method" instead of the "classical method" (see Esbensen and Reynolds, 1981), i.e., the daily fluxes are averaged; and

(2) monthly autospectra of the fluxes. For each month, an individual spectrum is estimated with the Maximum Entropy Method (MEM; e.g., von Storch and Fischer, 1983). We apply the MEM instead of the classical lag correlation method, since our time series are short (31 and 30 days, respectively), while the relevant time scales are up to, say: 20 days.

The comparison of the respective ensembles LF and the various FF's is done in terms of statistical tests: the monthly mean-ensembles are tested whether their expectations (= long year means) and their variances (= interannual variability of the monthly means), respectively, are consistent: this is done with the aid of the nonparametric Mann–Whitney and Siegel–Tukey test, respectively (e.g., Conover, 1971), with the null hypotheses "the expectation (variance) of the LF ensemble is equal to (smaller than) that of the FF ensemble" against the alternative "the expectation (variance) of the LF ensemble is not equal to (greater than) that of the FF ensemble". Since 8 tests are performed simultaneously for each FF-data set a rate of 1 erroneous rejection per FF data set is not unlikely (cf. von Storch (1982) or Livezey and Chen (1983)).

Furthermore, the mean autospectra are compared. To get a univariate problem, the spectra are projected onto the first EOF of the respective spectra at position E. This EOF was obtained without an a priori subtraction of the mean spectrum and thus shows the pattern of the long year mean spectrum. The resulting coefficients, denoted by $q$, of the LF- and FF-data set spectra are compared by means of the already mentioned Mann–Whitney test. Again, a one-sided test version is used because of the a priori considerations in the Introduction, that the variability of the DWD data sets is expected to be too small.

The risk applied is always 5%.

## 4. RESULTS

### *4.1. Expectation of monthly means (long year means)*

#### *4.1.1. Windstress*

The long year means for the 8 Atlantic weatherships obtained by the different FF methods are given in Table I.

*DWD analyses*: partly considerable differences between the momentum fluxes based on in-situ observations (LF) and those derived from large scale pressure and temperature fields (FF) are found. At weathership A, the differences are especially striking. The discrepancies of the zonal components at A and E are significant. The rate of rejections concerning the

TABLE I

Long year means of the components of the momentum fluxes at 8 weatherships

| Data set | A | B | C | D | E | I | J | K | Number of rejections |
|---|---|---|---|---|---|---|---|---|---|
| Zonal component of momentum flux, $\tau_x$ | | | | | | | | | |
| LF | 13 | 63 | 102 | 175 | 130 | 65 | 108 | 63 | – |
| FF Y | −56 * | 78 | 89 | 125 | 46 * | 77 | 81 | 64 | 2 |
| FF L3 | −78 * | 62 | 94 | 107 * | 56 * | 96 | 107 | 78 | 3 |
| FF L4 | −89 * | 72 | 108 | 122 | 62 | 114 | 123 | 84 | 1 |
| FF D3 | −74 * | 45 | 90 | 99 * | 50 * | 103 | 109 | 78 | 3 |
| FF D4 | −70 * | 76 | 81 | 100 * | 46 * | 81 | 88 | 71 | 3 |
| FF GCM | −96 * | −11 | 87 | 133 | 65 | 5 | 97 | 143 * | 2 |
| Meridional component of momentum flux, $\tau_y$ | | | | | | | | | |
| LF | 5 | −70 | 14 | 10 | 12 | 76 | 61 | 47 | – |
| FF Y | −18 | −12 * | 30 | 32 | 9 | 60 | 49 | 24 | 1 |
| FF L3 | −20 | −38 | 30 | 15 | 12 | 57 | 47 | 26 | 0 |
| FF L4 | −22 | −43 | 35 | 18 | 13 | 68 | 57 | 32 | 0 |
| FF D3 | 4 | −49 | 2 | −14 | −3 | 23 | 15 | 2 * | 1 |
| FF D4 | 5 | −57 | 2 | −17 | −4 | 26 | 19 | 3 * | 1 |
| FF GCM | −104 * | −36 | −23 | 13 | 33 | 26 * | −8 * | 8 | 3 |

FF-values univariately significant different from LF are marked by a star. The total number of univariately significant deviations is given in the last column. Units: $10^{-3}$ Pa.

meridional component is so small that these may be by chance. Measured in terms of the spatial average of the respective long year January means, all FF data produce a too weak stress (55–83% of LF, see Table II). L4 seems to yield the best results with 83% of the respective LF value. The inclusion of

TABLE II

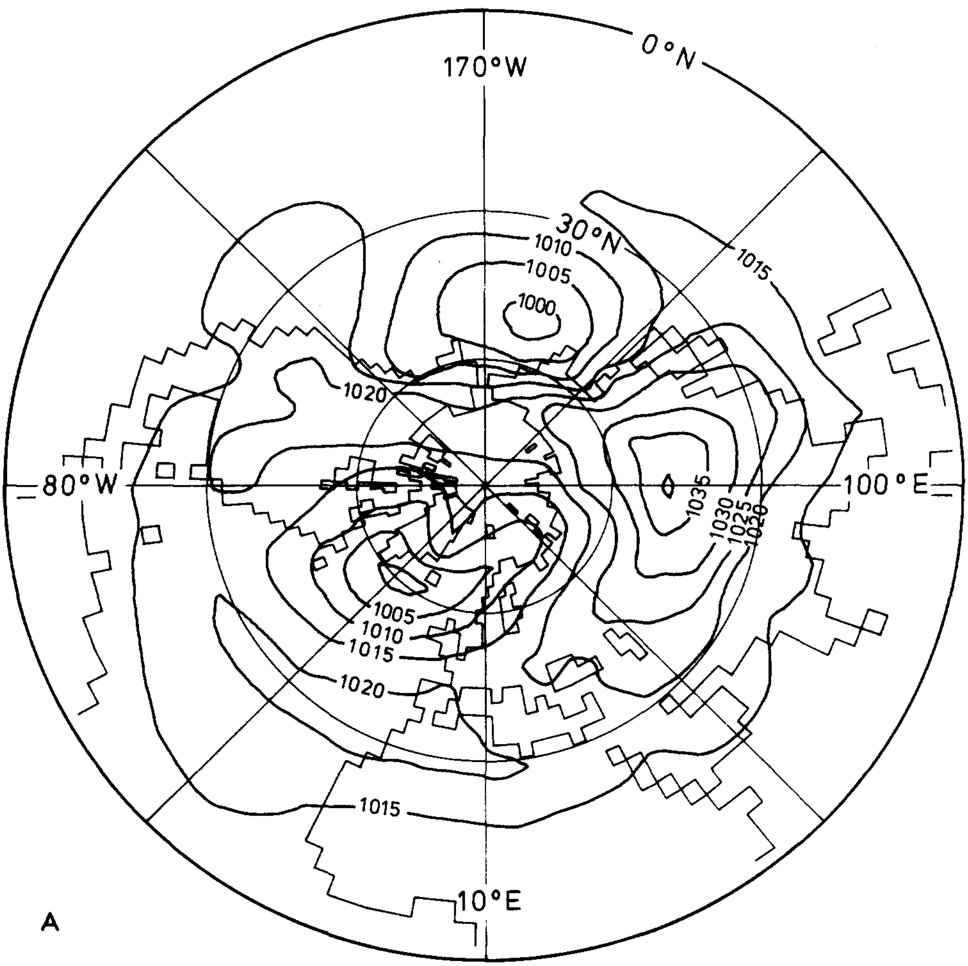
Long year means averaged over all 8 positions of the components of momentum and energy fluxes and ratios of absolute values of |FF|/|LF|

| Data set | Momentum flux | | | | Energy flux | | | |
|---|---|---|---|---|---|---|---|---|
| | $\tau_x$ | $\tau_y$ | $\sqrt{\tau_x^2 + \tau_y^2}$ | %LF | $H$ | $LE$ | $H + LE$ | %LF |
| LF | 90 | 20 | 92 | 100 | 48 | 124 | 172 | 100 |
| FF Y | 63 | 22 | 67 | 72 | – | – | – | – |
| FF L3 | 65 | 16 | 67 | 73 | – | – | – | – |
| FF L4 | 75 | 19 | 77 | 83 | – | – | – | – |
| FF D3 | 63 | −3 | 63 | 69 | – | – | – | – |
| FF D4 | 73 | −3 | 73 | 81 | – | – | – | – |
| FF GCM | 53 | −18 | 58 | 60 | 15 | 124 | 139 | 80 |

Units: $10^{-3}$ Pa and $Wm^{-2}$.

the static stability (in Y) does not give more realistic long year mean momentum fluxes, but the application of an $U$-dependent drag coefficient (i.e., of (4) instead of (3)) increases the strength of the fluxes clearly. In terms of the mean absolute value of the stress vector (see Table II) and the numbers of significant deviations LF–FF (see Table I), L4 yields the best results. The reasons for the confirmed LF–FF discrepancy at A and E are unknown. One may speculate that at A it is related to the location at or somewhat north of the centre of the quasistationary Icelandic Low (see Fig. 2a), an area with enhanced cyclogenesis (Whittaker and Horn, 1982, p.18).

*GCM generated fluxes*: the GCM results are significantly different from LF at the positions A, I–K, which can partly be related to a shift of the simulated quasistationary Icelandic Low somewhat eastward (see Fig. 2b).




A

Seemingly, the quality of the monthly averaged GCM FF-data is worse than the FF-data based on routine DWD-analyses. This is displayed by the rate of only 60% of the spatially averaged strength of momentum flux "FF GCM"/"LF"; see Table II.

*4.1.2. Energy fluxes*

The results for the individual weatherships are given in Table III, the spatially averaged numbers are included in Table II. Only GCM generated FF data are available (though principally *H* and *LE* could be estimated with

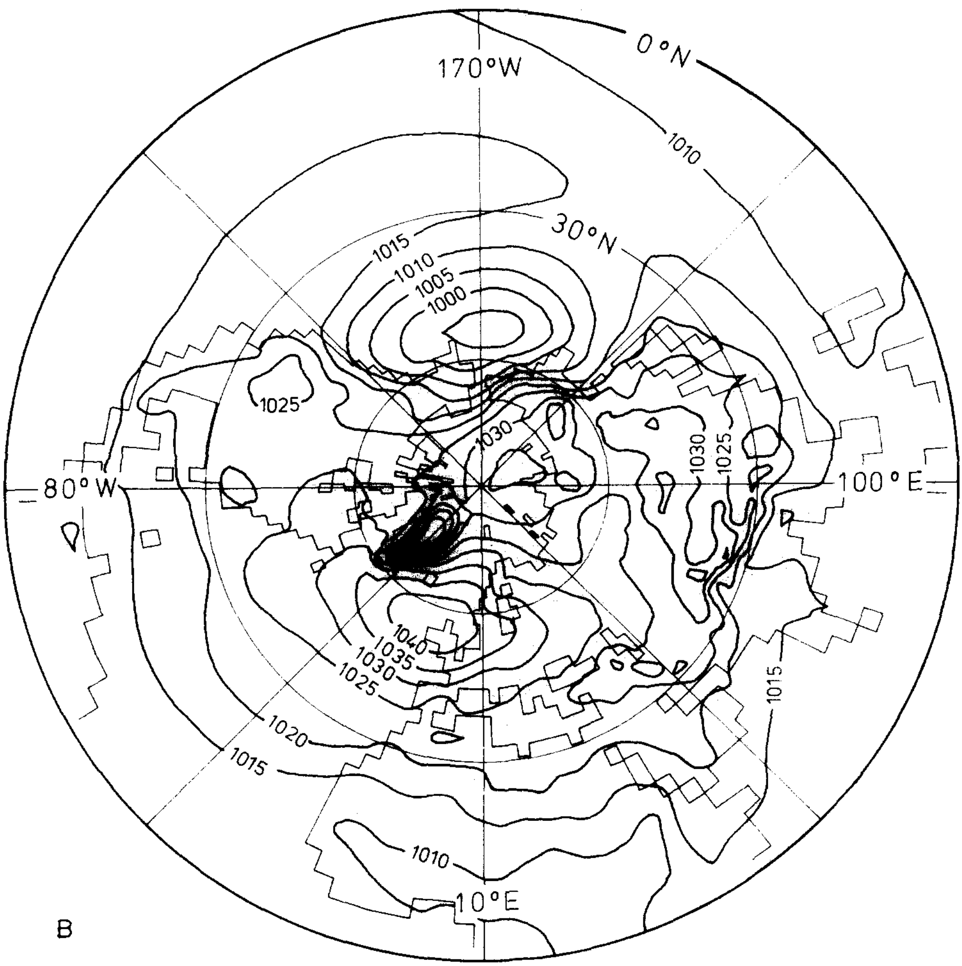



Fig. 2. (a) January mean (1967–83) of sea surface pressure. Spacing: 5 mbar (b) 300 day average of the GCM generated January sea surface pressure field. Spacing: 5 mbar. (From Assmann, 1983)

TABLE III

Long year means of latent and sensible heat fluxes at 8 weatherships

| Data set | Weatherships | | | | | | | | Number of rejections |
|---|---|---|---|---|---|---|---|---|---|
| | A | B | C | D | E | I | J | K | |
| Sensible heat flux, *H* | | | | | | | | | |
| LF | 56 | 94 | 31 | 82 | 28 | 54 | 33 | 8 | – |
| FF GCM | 25 * | −5 * | 17 | 56 * | 10 * | 13 * | 17 * | −14 * | 7 |
| Latent heat flux, *LE* | | | | | | | | | |
| LF | 91 | 102 | 86 | 223 | 184 | 115 | 105 | 85 | – |
| FF GCM | 112 * | 37 * | 102 * | 223 | 166 | 103 | 117 | 131 * | 4 |

Univariately significant differences LF–FF are marked by a star, the total number of which is given in the last column. Units: $Wm^{-2}$.

the aid of Y from standard analyses). The flux of sensible heat, *H*, is significantly too small (on an average only 31% of the respective LF data) at most positions. The latter is likely caused by an overall increase of the temperature at the models lowest level, 850 mbar. The situation at B is badly represented especially: one reason might be a too cold SST used in the GCM at this location, another the insufficiently modelled advection of polar cold air masses (see Fig. 2). The latent heat flux, *LE*, deviates significantly also from LF, but this is not due to a general over- or underestimation. At B, the flux is very weak in coincidence with *H*, but at A and K the significance is accompanied simultaneously with a significant decrease of sensible heat flux. The ratio "FF GCM"/"LF" of the spatial averages is 100%. The total energy flux given as spatial average is reduced to 80%, which is likely insignificant.

### 4.2. *Variability of the monthly means*

Owing to the relation (1), one expects a priori the schemes D3 and L3 to give a variability at all time-scales smaller than D4 and L4, respectively. Furthermore, as outlined in the Introduction, it is hypothesized that all DWD based FF data sets exhibit a reduced variability. Owing to these two arguments and the results concerning the long year means, we renounce in the following to discuss the results with the constant drag coefficient (3) (which follow expectation).

#### 4.2.1. *Windstress*

*DWD-analyses*: the interannual standard deviation is reduced for all parameterizations at all positions. Often this reduction is significant. (Table IV)

TABLE IV

Interannual variability of January monthly means of momentum fluxes

| Data set | Weatherships A | B | C | D | E | I | J | K | Average | %LF | Number of rejections |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Zonal component of momentum flux, $\tau_x$ | | | | | | | | | | | |
| LF | 98 | 161 | 178 | 101 | 113 | 119 | 160 | 109 | 130 | 100 | – |
| FF Y | 52 | 106 | 74 * | 86 | 56 | 82 | 57 * | 36 * | 69 | 53 | 3 |
| FF L4 | 66 | 106 | 92 * | 74 | 76 | 107 | 84 * | 61 | 83 | 64 | 2 |
| FF D4 | 59 | 84 | 86 * | 62 | 65 | 107 | 80 * | 66 | 76 | 58 | 2 |
| FF GCM | 38 * | 34 * | 43 * | 37 * | 24 * | 39 * | 52 * | 36 | 38 | 29 | 7 |
| Meridional component of momentum flux, $\tau_y$ | | | | | | | | | | | |
| LF | 106 | 98 | 81 | 83 | 50 | 104 | 85 | 63 | 84 | 100 | – |
| FF Y | 51 * | 42 | 35 * | 47 * | 25 * | 77 | 70 | 47 | 49 | 59 | 4 |
| FF L4 | 62 | 67 | 48 * | 59 * | 39 | 68 | 65 | 55 | 55 | 65 | 2 |
| FF D4 | 62 | 89 | 44 * | 66 | 41 | 65 | 64 | 38 | 59 | 70 | 1 |
| FF GCM | 35 * | 18 * | 41 * | 35 * | 11 * | 37 * | 29 | 33 * | 30 | 36 | 7 |

Univariately significant deviations are marked by a star, the total number of which is given in the last column. Units: $10^{-3}$ Pa.

On average, the results obtained from Y are the worst in this respect. The parameterizations utilizing only the SLP, namely L4 and D4, yield similar results: though they are superior to those obtained by Y, they exhibit partly strong underestimations. The |FF|/|LF|-ratios are 53–59% for Y and 58–70% for D4 and L4. The central positions D (meridional component) and C and the easterly J (zonal component) seem to be misrepresented especially. At C, this fact is possibly related to the high cyclone frequency (cf. Whittaker and Horn, 1982).

*GCM-generated data*: the GCM-generated interannual variability is reduced significantly compared to the LF-data. Averaged over all positions, the data set variability "FF GCM" is only 29% and 36% of that of LF, which is worse than all the ratios obtained with the DWD data set. The reason may be found in deficiences of the model's general circulation, which was found to exhibit an overall reduction of the interannual variability of the stationary eddies (von Storch and Roeckner, 1983).

### *4.2.2. Energy fluxes*

Again, only values of the data set "FF GCM" are available. At all positions, the GCM generated interannual variability of the monthly mean energy fluxes is reduced (see Table V), which is significant in many cases. On average, it is only 50% ($H$) and 65% ($LE$) of the respective LF data variability.

TABLE V

Interannual standard deviation of January monthly means of energy fluxes

| Data set | Weatherships A | B | C | D | E | I | J | K | Average | %LF | Number of rejections |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Sensible heat flux, *H* | | | | | | | | | | | |
| LF | 20 | 44 | 21 | 31 | 13 | 22 | 14 | 10 | 22 | 100 | – |
| FF GCM | 10 * | 12 * | 8 | 21 | 9 | 10 * | 9 * | 7 | 11 | 50 | 4 |
| Latent heat flux, *LE* | | | | | | | | | | | |
| LF | 24 | 31 | 21 | 53 | 48 | 25 | 24 | 27 | 32 | 100 | – |
| FF GCM | 13 * | 13 * | 14 | 38 | 43 | 13 | 19 | 13 * | 21 | 65 | 3 |

Univariately significant deviations are marked by a star, the total number of which is given in the last column. Units: $Wm^{-2}$.

### 4.3. *Monthly autospectra*

The results concerning the monthly autospectra of $\tau$, the momentum fluxes at the 8 positions, are given in Table VI in terms of the mean coefficient $q$ (see section 3). All spectra exhibit a significant reduction.

*DWD-analyses*: the reduction of the spectral density is evident for scales shorter than, say 12 days, and is maximum for the smallest resolved timescale, 2 days. This alludes to the insufficient inclusion of the intensity of cyclones and their fronts in the regular DWD-analyses. The best, though still underestimating, results are obtained by L4 and D4 at the northeasterly positions I and J, at the easterly K and the northwesterly B. On the other hand, bad results are obtained at the southernmost position E, where the distance to the next meteorological stations is large, with 20% maximally. The spectra at the central position C in the vicinity of cyclone activity (cf. Whittaker and Horn, 1982) with 12–21% are also unsatisfying. On average, Y gives the worst results, namely 22% in terms of the mean $q$, L4 yields 27%, which is insignificantly more than 25% obtained by D4.

*GCM-generated data*: it turns out that the GCM generated spectral density is reduced for all time scales. In accordance with the above stated evident reduction of the variability of monthly means, the decrease is maximum for the largest resolved timescales (~ 15–30 days). For the synoptic time scale (up to 10d), however, the GCM generated spectra exhibit partly variances larger than those of the DWD based FF data sets. For instance, the 11 (9, 8) units obtained at D (J, K) for the zonal component is a maximum of the FF data at these positions. At A, the 4 (3) units for the zonal (meridional) component compare to values of the DWD based data sets. On the other hand, the results at B and E are poor. On average, the rate

TABLE VI

Mean coefficients $q$ of the first EOF of the monthly spectra at E, which shows the interannual mean pattern

| Data set | Weathership | $\tau_x$ | %LF | $\tau_y$ | %LF |
|---|---|---|---|---|---|
| LF | A | 31 | 100% | 18 | 100% |
| FF Y | | 4 | 13% | 3 | 17% |
| FF L4 | | 6 | 19% | 4 | 22% |
| FF D4 | | 6 | 19% | 4 | 22% |
| FF GCM | | 4 | 13% | 3 | 17% |
| LF | B | 37 | 100% | 25 | 100% |
| FF Y | | 7 | 19% | 6 | 24% |
| FF L4 | | 8 | 22% | 11 | 44% |
| FF D4 | | 6 | 16% | 10 | 40% |
| FF GCM | | 2 | 5% | 1 | 4% |
| LF | C | 33 | 100% | 24 | 100% |
| FF Y | | 4 | 12% | 3 | 13% |
| FF L4 | | 5 | 15% | 5 | 21% |
| FF D4 | | 5 | 15% | 5 | 21% |
| FF GCM | | 6 | 18% | 4 | 17% |
| LF | D | 39 | 100% | 30 | 100% |
| FF Y | | 7 | 18% | 6 | 20% |
| FF L4 | | 6 | 15% | 7 | 23% |
| FF D4 | | 4 | 10% | 8 | 26% |
| FF GCM | | 11 | 28% | 9 | 30% |
| LF | E | 20 | 100% | 18 | 100% |
| FF Y | | 2 | 10% | 2 | 11% |
| FF L4 | | 4 | 20% | 2 | 11% |
| FF D4 | | 4 | 20% | 2 | 11% |
| FF GCM | | 3 | 15% | 1 | 6% |
| LF | I | 27 | 100% | 15 | 100% |
| FF Y | | 7 | 26% | 6 | 40% |
| FF L4 | | 9 | 33% | 6 | 40% |
| FF D4 | | 9 | 33% | 4 | 27% |
| FF GCM | | 4 | 19% | 2 | 13% |
| LF | J | 19 | 100% | 18 | 100% |
| FF Y | | 5 | 26% | 7 | 38% |
| FF L4 | | 5 | 26% | 8 | 44% |
| FF D4 | | 5 | 26% | 9 | 50% |
| FF GCM | | 9 | 47% | 4 | 22% |
| LF | K | 15 | – | 8 | – |
| FF Y | | 4 | 26% | 3 | 38% |
| FF L4 | | 6 | 40% | 3 | 38% |
| FF D4 | | 6 | 40% | 2 | 25% |
| FF GCM | | 8 | 53% | 5 | 63% |

Dimensionless units.

"FF GCM"/"LF" is 23%, which is comparable with the Y-rate. Similar results hold for the spectra of the energy fluxes.

## 5. CONCLUSION

Stress should be laid upon the fact that these conclusions hold only for DWD analyses and simulated Januaries generated with the Hamburg University GCM.

We investigated how realistic the atmospheric forcing at the oceanic surface by means of different FF data sets is: if long year means are needed, all presented FF data sets seem to be suited, though the GCM data considered in this study are somewhat worse than the FF data sets based on daily DWD-analyses. L4 and D4 seem to give the best mean momentum fluxes.

When compared in terms of individual monthly means, it is found that the interannual variability of the fluxes is reduced for all FF data sets. The best results are again obtained by L4 and D4. Among the DWD based data set, Y amounts in the weakest interannual variability.

The study of the monthly autospectra yields a too low spectral density for time scales 12 days (Y, D and L) and for all time scales (GCM).

The consequences for the application of FF-data as oceanic forcing are:

(1) if only windstresses are needed, methods L4 and D4 yield the best but still too weak forcing of the ocean; and

(2) the GCM generated data show poor variability at longer time scales in the particular area under concern in this study. The intensity of the synoptic scale disturbances is partly better than that of the DWD based data sets.

At present, the available data allow a realistic transient forcing of the ocean only to a limited extent. In case of the GCMs, progress is to be expected in the course of the improvement of included physical processes, while in case of the analyses, some future remote sensing techniques (cf. WCRP, 1984) may result in better surface wind data. Furthermore, attempts are made to improve the analyses by multivariate local fit (Luthardt, 1982).

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