Estimates of Surface Fluxes from Global Operational Numerical Weather Predictions

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Estimates of surface fluxes from global operational numerical weather predictions

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The success of coupled models of the ocean–atmosphere system depends in part on their ability to estimate the momentum, heat and water vapour fluxes at the interface accurately. Their accuracy as now calculated by atmospheric numerical forecast models with relevant variables at the sea surface given is uncertain. The achievement of an acceptable accuracy in this simpler situation is an essential preliminary to a solution of the more difficult interactive problem.

The ISCU/WMO Joint Scientific Committee (JSC) for the World Climate Research Programme (WCRP) considered how best to obtain surface flux values primarily for running large-scale ocean models. They concluded that the most promising approach was to extract them from numerical prediction models whose capabilities in terms of assimilating observations of many diverse kinds and of quality controlling meteorological information, have reached a high level of development and are being improved continuously. The committee requested its Working Group on Numerical Experimentation (WGNE) to investigate and report on the accuracies now achieved.

In the absence of measurements of surface fluxes suitable for validation, the WGNE decided that the first step was to compare surface fluxes as estimated by state-of-the-art global prediction models. The ECMWF (European Centre for Medium-Range Weather Forecasts) and Meteorological Office models were considered suitable, and have the advantage of employing different approaches to data assimilation, model configuration and the parametrization of physical processes. This report will outline the results obtained by the two models for a first comparison period, May–June 1987.

INTRODUCTION

The exchange of momentum, sensible heat, water vapour, radiation and fresh water at the surface of the ocean has to be estimated accurately for a variety of purposes within the World Climate Research programme. The tropical-ocean–global-atmosphere (TOGA) programme concerned with the real time prediction of the influence of the tropical oceans on the global atmosphere clearly is crucially dependent on a correct simulation of ocean fluxes. At the longer timescales of the World Ocean Circulation Experiment (WOCE) programme a reliable ocean simulation is equally reliant on accurate fluxes and even Stream 1 concerned essentially with atmosphere prediction over extended periods requires for many purposes that the fluxes are reasonably well estimated.

The Working Group on Numerical Experimentation (WGNE) was asked by the Joint Scientific Committee (JSC) for the World Climate Research Programme (WCRP) to report on the quality of fluxes now available from operational global prediction models, in order that informed decisions might be made by JSC on the extent to which new observations or observation systems might be required to achieve the objectives of the WCRP. The only global models that could provide surface flux estimates readily on a short timescale were those operated at the European Centre for Medium Range Weather Forecasts (ECMWF) and at the Meteorological Office (MO) at Bracknell. The results presented here concern only these two models, although the project is currently being extended to cover a larger number of operational models. At the time of writing results are also being received from the National Meteorological Center, Washington.

The two models are an appropriate choice for comparison in that the differences in formulation between them are probably as great or greater than between any pair of operational global models. The main differences are as follows.

1. Numerically, the ECMWF model is formulated spectrally, the MO model in finite differences.

2. The main parametrizations concerned with the planetary boundary layer, radiation and convection are independently developed. The convection schemes give notably different simulations in the tropics.

3. ECMWF assimilates observations by the use of optimum interpolation techniques, followed by nonlinear normal mode initialization; the MO system depends on the repeated insertion of observations over a period.

4. The quality-control procedures and the criteria for accepting or rejecting observations (which can be a crucial matter in creating accurate meteorological analyses) have notable differences; in particular, the British system is more dependent on manual intervention.

PROCEDURE

The object of the exercise was to compare the fluxes actually used within the atmospheric models and not fluxes derived anew from analyses. Further investigations showed that to achieve stability it was necessary to average the fluxes over a period of the model integration. For the fluxes compared below, daily average values were obtained somewhat differently for the two systems, as follows.

(*a*) *ECMWF*

Starting from an analysis for mid-day the fluxes are accumulated time step by time step for the first 12 h of a forecast, and these are taken to provide the daily average value.

(*b*) *MO*

Data assimilation is carried out every 6 h. To provide a background or initial-guess field for the assimilation, a forecast is run for 6 h from the previous analysis. During each 6 h forecast, the fluxes are accumulated, and a daily average obtained by averaging the four periods of 6 h.

At the beginning of the comparison the fluxes were not being archived routinely and a number of comparisons were done by using the values for a particular day calculated anew. Reasons for differences were identified as far as possible. By May 1987, routine archiving of fluxes had been implemented at both centres. A period of four weeks from mid-May to mid-June 1987 covering the onset of the southeast Asian monsoon was then chosen for a comparison. The month of February 1988 followed by other months are currently being compared.

Initially, emphasis has been on the fluxes of momentum for which there is likely to be the greatest commonality between the models. Some comparisons of sensible and latent heat fluxes have also been made, but it is clear that more detailed consideration of the reasons for the differences between them still needs to be carried out. It is intended that the comparison will be extended to the remaining fluxes, and to as many global models as possible, as the opportunity arises.

Reasons for differences in model estimates of fluxes

Until recently ocean–atmosphere fluxes have not, in general, been subjected to close scrutiny in numerical models. On the whole the quality of short-range and medium-range forecasts have not been demonstrated to be very sensitive to the quality of the fluxes, and therefore they have not received the attention in weather forecasting models that they have in climate models. For that reason the fluxes may sometimes be affected by model shortcomings that, once attention has been drawn to them, can be removed without difficulty. One can therefore expect that the process of examining and comparing fluxes will itself lead to significant improvement of the estimates over the next few years.

Leaving aside these avoidable causes of differences between models the main reasons for significant differences are the following.

(*a*) *Dependence on observation density*

Where the number of observations available is reasonably large and of good coverage, one can expect modern forecasting systems to produce very similar analyses of the primary variables: pressure, temperature and wind. This should translate to similarities in the fluxes, although, mainly for the reasons indicated below, there may still be significant differences. However, over large parts of the oceans the number of observations is insufficient to define the analyses closely, and the models, other things being equal, will tend over a period towards their individual estimates of the climatology. The areas where this problem is likely to be greatest are in the tropics and over the southern oceans though it may be noted that there are frequently parts of the N Atlantic and N Pacific where the observational coverage is clearly inadequate.

The difficulties concerning observations are illustrated in figures 1 and 2, which show for the Indian Ocean the average number of observations available per day from ships and satellite winds, respectively, that might be expected to determine and constrain the flux estimates. It is very clear that for long periods the density of observations is insufficient and for the Indian Ocean we must expect that the model analyses will tend rather heavily towards the models' climates.

The implication is that systematic errors characteristic of a model's climatology may be evident in its estimates of surface fluxes. For example, in a comparison of systematic errors in models carried out in cooperation with WGNE, there is some evidence that the ECMWF model climatology may tend to underestimate the strength of subtropical easterlies, and this may be reflected in the flux results shown later.

(*b*) *Analysis systems*

Modern analysis systems use a background or first-guess field for the analysis time as the starting point for the assimilation of observations at that time. In determining the new analysis, weights related to their respective error characteristics are ascribed both to the observations

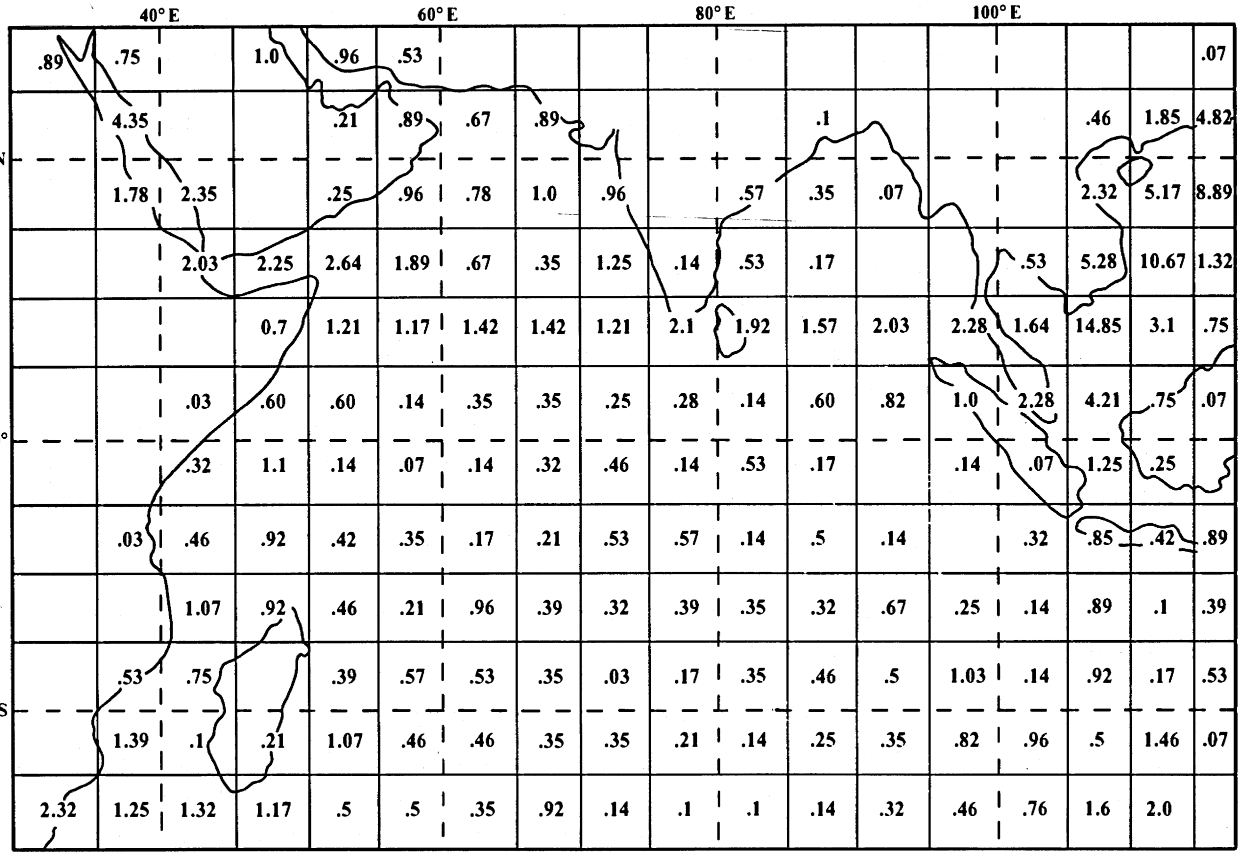

FIGURE 1. The average number of ship observations received at the Meteorological Office, Bracknell per day during the period 16 May to 12 June 1987. Values are for numbers of observations per five degree square.

and to the background values. The system also determines an area around the observation that it is allowed to influence. Especially in poorly observed regions, analysis differences due to differences in the effective radius of influence and the closeness of fit to observations (determined by the weight) are very evident. The greater the area of influence the 'smoother' the analyses in sparse data regions tend to become, but the greater the danger of missing small-scale features. This probably accounts for many of the differences between ECMWF and MO analyses in the tropics where the systems depicted in ECMWF fields are generally on larger scales.

(*c*) *Forecast model formulations*

The algorithms used for surface fluxes differ from model to model. For the calculations shown in this paper, the MO model used a constant drag coefficient, determined on the basis of the Monin–Obhukov similarity relations for the atmospheric surface layer, and assuming a roughness length z_0 of 10^{-4} m. On the other hand, the ECMWF formulation used a roughness length varying with wind speed as proposed by Charnock (1955)

$$z_0 = \frac{0.032 C_D |V_1|^2}{g},$$

where C_D is the drag coefficient and V_1, the wind velocity at the lowest model level. In figure 3 the drag coefficients in the two models at different wind speeds and Richardson number are compared. At high wind speeds the ECMWF value is substantially greater than the MO value.

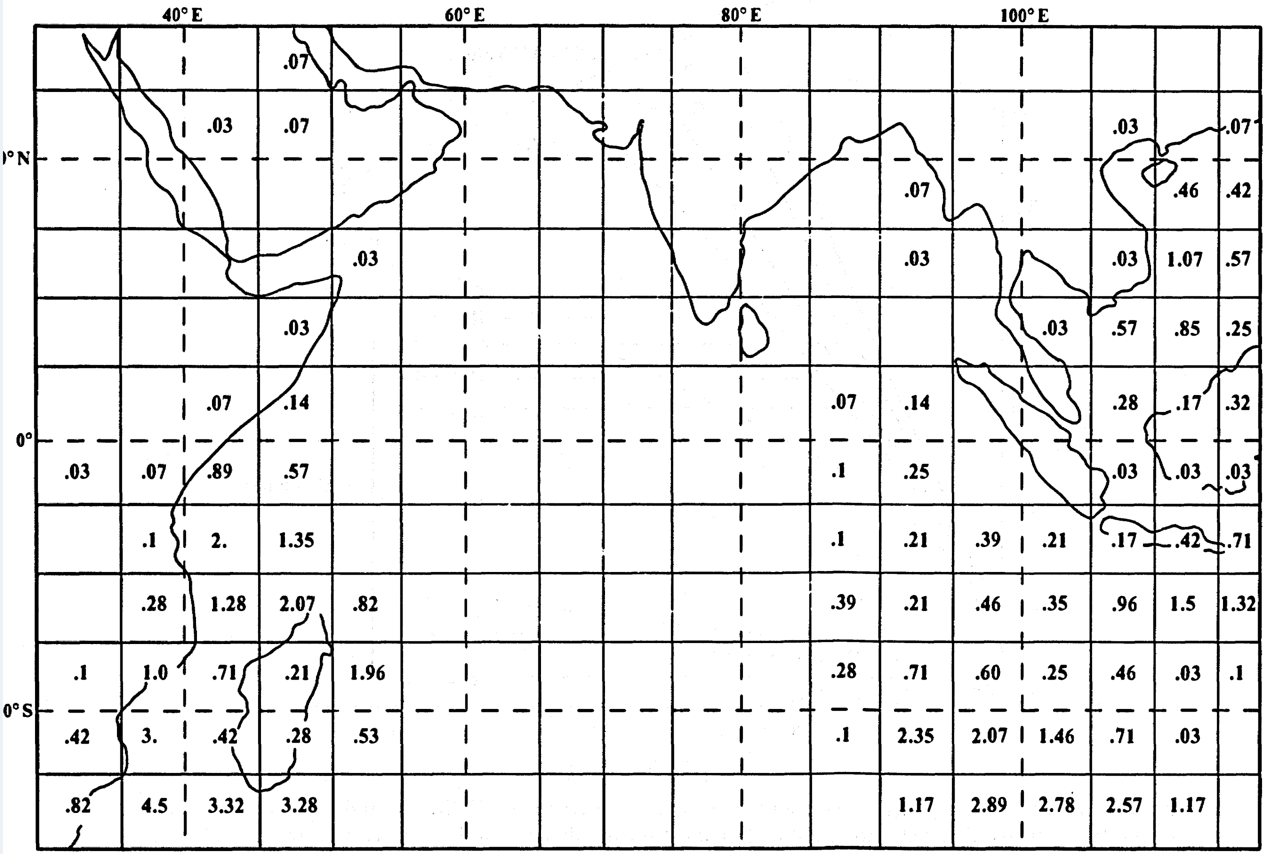

FIGURE 2. As figure 1 but for low level satellite winds (SATOBS).

(*d*) *Model transients*

The assimilation of data into numerical models creates transient changes in the model variables as the model adjusts to the new data. There are numerous sources for the transients. Their nature depends critically on the formulation of the model and on the details of the assimilation system. An obvious case where an adjustment has to take place is when a weather system in the background forecast has been misplaced or not detected. The observations may well indicate the error, but they are unlikely on their own to define the system with its proper intensity and position. There is likely to be a period when the model is, in effect, making all the variables associated with the system, including for example the vertical velocity, consistent with one another.

Some transients are associated with model systematic errors. For example, if the boundary layer and convective parametrizations in a model tend to create a low-level atmosphere that is too moist, then the effect of assimilating humidity observations may be to produce relatively dry areas that rapidly become moister in the initial stages of the forecast period. Important dynamical reasons for such transient effects in models have been identified, notably: (i) the lack of initial 'balance' between the wind and mass fields, which causes variations in the wind due to inertial or gravity waves and is likely to be a factor in the MO flux values and (ii) the reduction in vertical velocity and convergence which is often produced by initialization procedures, and could therefore affect the ECMWF momentum flux values.

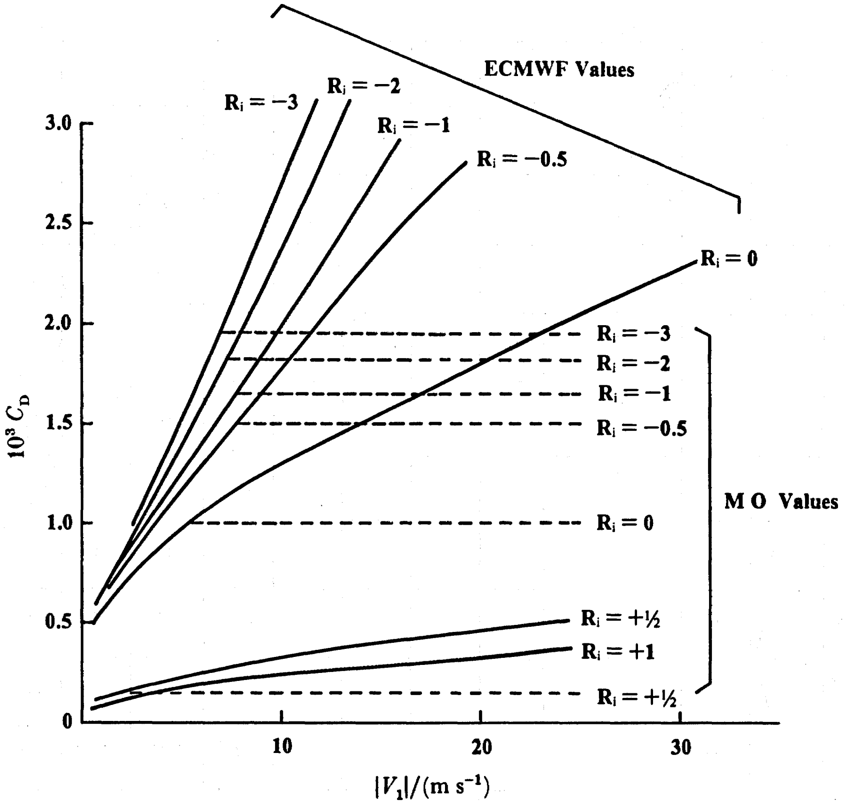

Figure 3. Comparison of the drag coefficients over the sea used in the ECMWF and MO models, showing the dependence on wind speed and stability (Richardson number in the lowest layer). For the MO model, the values are constant with windspeed. (Values derived from Bell & Dickenson, 'The Meteorological Office operational numerical weather prediction system', Meteorological Office Scientific Paper no. 41, HMSO and Research Manual 3, ECMWF, using 30 m as the height of the lowest model level.)

The formulations discussed in (*c*) above may themselves give rise to transient effects. If the stress is overestimated, the low-level wind becomes weaker in the initial stages of a forecast. In principle, it should be possible to determine if there are systematic effects of this kind by comparing forecast winds at 6 h with observations. If there is a tendency to underestimate the winds it is probable that the stress has been too great. It may be noted, however, that the first-order effect of errors of this kind is to restore the stress to its correct value.

RESULTS

(*a*) *Surface wind stress*

The values of the stress for the four-week period 16 May to 12 June 1987 are illustrated for three tropical areas for the two operational numerical weather forecasting systems in figures 4–6. Values in Northern Hemisphere middle latitudes (not illustrated) tend to show a smaller divergence between the models, the main differences being largely attributable to the differences in formulation noted in (*c*) above; or, occasionally, to the lack of observations in some areas though differences for this reason tend to be greatly reduced by the averaging process.

For the tropical Atlantic (figure 4) the stress patterns and levels obtained by the two models

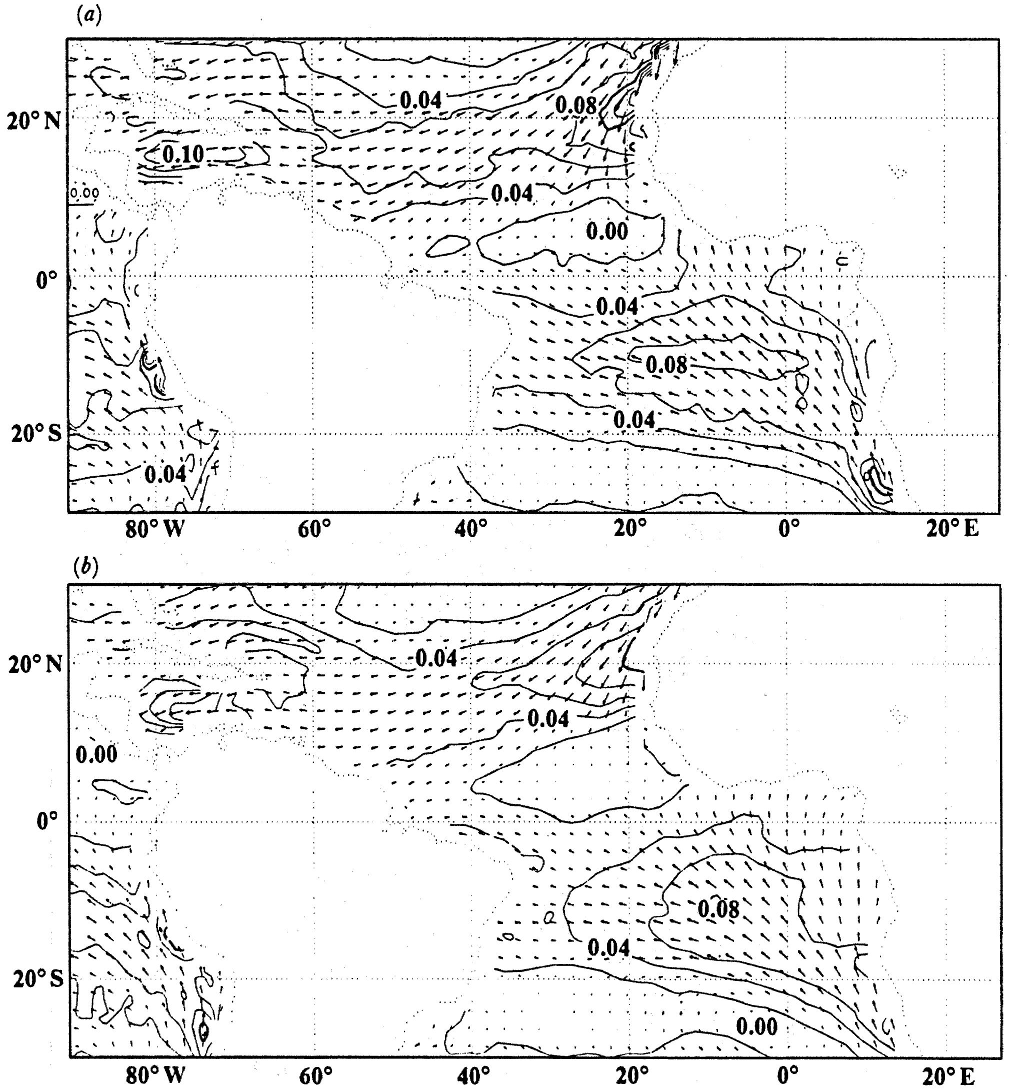

FIGURE 4. Values of the surface stress derived from the Meteorological Office (*a*) and ECMWF (*b*) models for the period 16 May to 12 June 1987, for the tropical Atlantic Ocean. (Arrows indicate the direction and strength of the low-level wind. Isopleths are at intervals of 0.02 N m^{-2}. The 0.1 isopleth is thickened).

are very similar. The most obvious differences are those that may be attributed to the assimilation techniques, which favour much smoother fields in the ECMWF (figure 4*b*) than in the MO (figure 4*a*) estimates.

For the Indian Ocean (figure 5) the differences are larger, but, given the striking paucity of observations in the area noted in figures 1 and 2, the extent of the agreement is greater than might have been expected. An interesting feature is the MO maximum in the Arabian Sea (figure 5*a*), further north and further from the coast than the ECMWF maximum (figure 5*b*). Climatology tends to support the latter, but it is not yet clear whether the difference is associated with the particular year or is a systematic error in one or other of the models. A question of especial importance in considering the estimates for this area is whether or not the agreement between the models is greater than between either and reality; that is, whether the agreement is the result only of agreement between their model climatologies. Clearly this

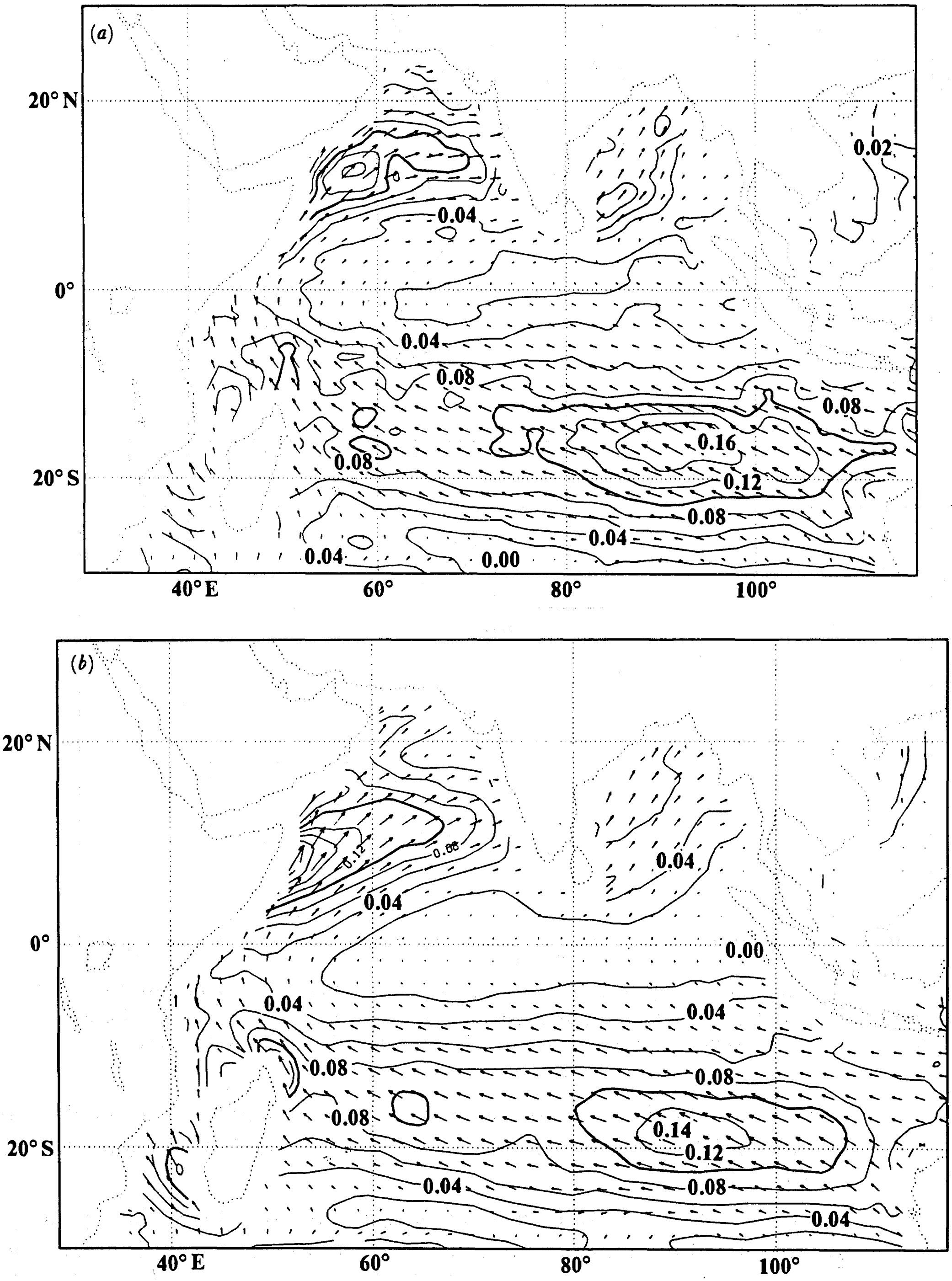

FIGURE 5. As for figure 4 for the Indian Ocean.

cannot be answered convincingly without a larger number of observations to define the atmospheric circulation.

The tropical Pacific Ocean (figure 6) shows, in the main, the same features that have been noted for the other two oceans. The MO estimates (figure 6*a*) have greater small-scale variability and tend to be the larger, significantly so in the Northern Hemisphere trades.

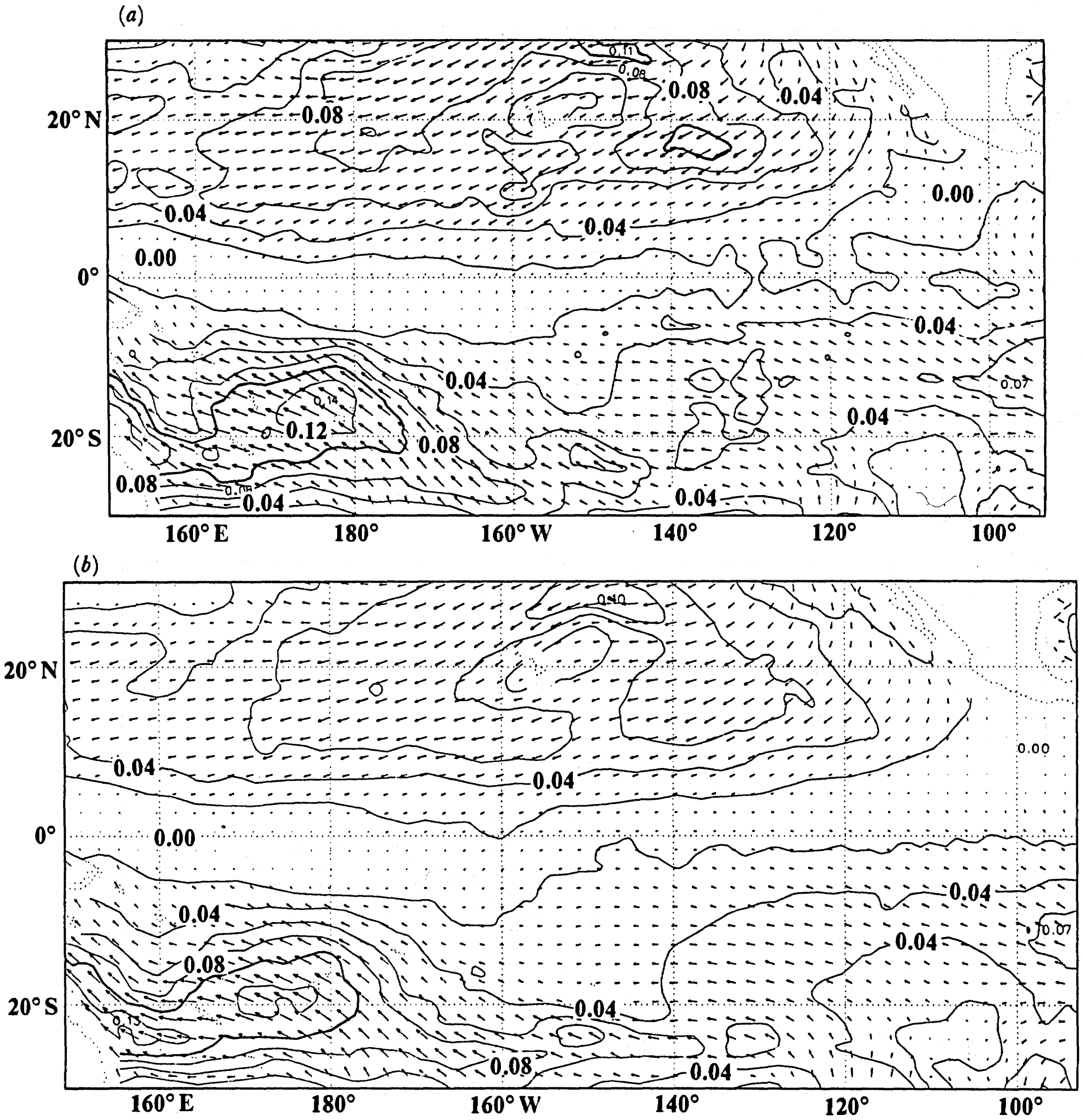

FIGURE 6. As for figure 4 for the Pacific Ocean.

(b) *Latent heat fluxes*

Sensible heat fluxes in the tropics are usually small relative to the latent heat fluxes, and have therefore not been illustrated. The latent heat fluxes are shown in figures 7–9, for the same areas and formats as figures 4–6.

An important difference between the estimates of latent heat fluxes and stresses is that whereas the observations of winds, which determine the stress, are assimilated into the forecasting models, ship's observations of temperature and humidity, which could in principle be assimilated, are not. It is evident from an examination of the observations that most ship measurements are insufficiently accurate for the purpose, primarily because of the influence of radiation from the ship's hull. It is possible that a selection of special ships or night-time observations from a larger number of ships could provide useful air-temperature information. This would be a most significant step in achieving acceptable flux estimates, but the possibility

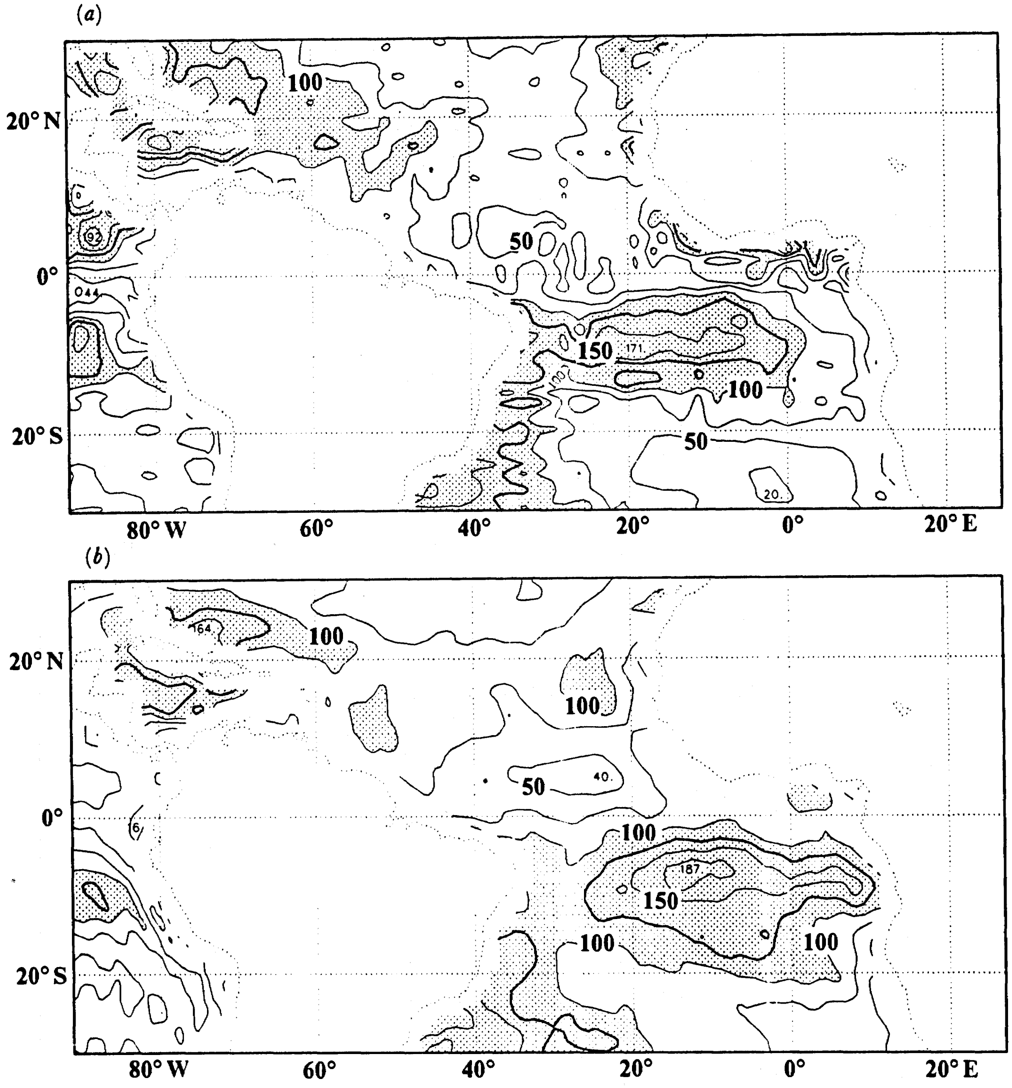

Figure 7. Values of latent heat flux, otherwise as figure 4.

has not, we believe, been explored. In the meantime it is important to realize that the temperature and humidity differences between the sea and the first model level are not constrained by observations but are determined by internal adjustments within the models.

In examining the latent heat fluxes from the MO model, two readily avoidable features that have a large influence on the results were identified. (i) The sea surface temperature (SST) fields, obtained by assimilating observations of SST each day and not as is more commonly done assembling observations over a period of five days or so, contain small but significant roughnesses. At the high temperatures of the tropical oceans these lead, because of the sensitivity of the saturation vapour pressure to temperature, to substantial roughnesses in the latent heat fluxes. (ii) At the time of the comparison, the addition to the operational programme to allow rainfall to moisten layers lower than the first layer below cloud base had not been made. In consequence it is possible to obtain, simultaneously, large values of rainfall and large values of surface evaporation. These shortcomings have to be borne in mind in examining the results.

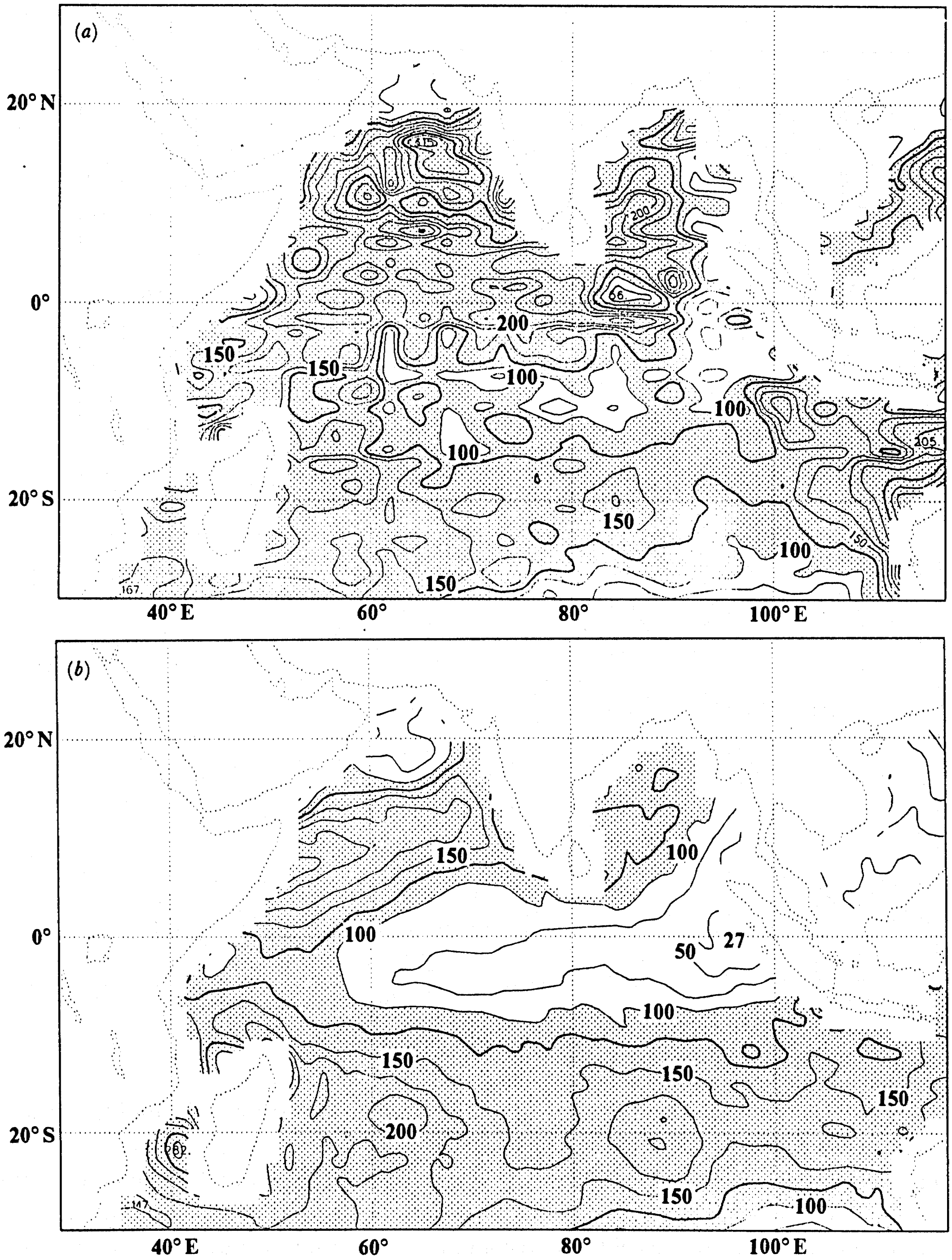

FIGURE 8. As for figure 7 for the Indian Ocean.

The latent heat fluxes for the tropical Atlantic are shown in figure 7. The SST values are on the whole lower at this time of year than in parts of the Indian and Pacific Oceans; further, the Intertropical Convergence is comparatively weak with less precipitation than many parts of the tropics. The shortcomings in the MO model are therefore less serious in this area, and the agreement between the model estimates is reasonable, especially recollecting the difficulties

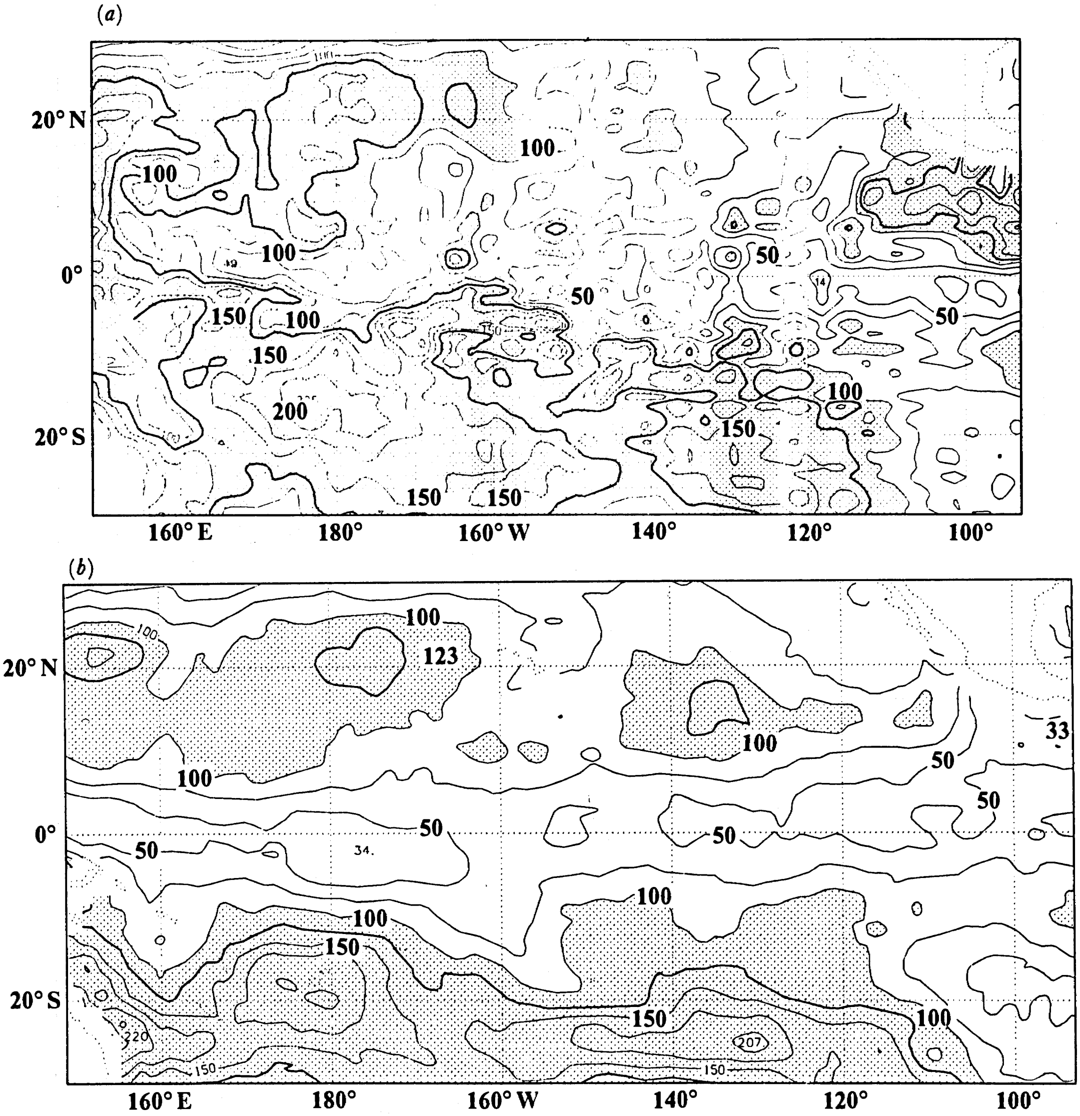

Figure 9. As for figure 7 for the Pacific Ocean.

in providing accurate estimates of the vertical gradients of temperature and humidity close to the tropical sea surface.

Comparison of the Indian and Pacific Ocean estimates (figures 8 and 9)is difficult because of the excessive noisiness of the MO values. Apart from noting that there is a basic similarity of pattern it is not possible on this evidence to comment further on the quality of the estimates.

Conclusions

The comparison of fluxes from operational forecasting models needs to be an ongoing activity in order to establish whether the characteristics noted here are generally valid, and how the agreement among models improves with time. Greater agreement among models, and between models and reality, is to be expected both as a result of developments in model formulation and assimilation systems and because of the availability of additional observations such as those from the *ERS*-1 satellite. It is generally accepted that the best estimates of surface fluxes will come from numerical forecasting systems capable of assimilating all observations in an optimum way.

An important spur to improve model flux estimates will come from the results of ocean model integrations with the values supplied by forecasting models to provide the atmospheric forcing. In this regard, research with ocean models at the National Meteorological Center, Washington, and at the Hooke Institute, Oxford, are particularly notable.

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