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Surface fluxes from short range forecasts

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SURFACE FLUXES FROM SHORT RANGE FORECASTS

1. INTRODUCTION

The fluxes of momentum, sensible heat, water vapour, radiation and fresh water at the surface of the atmosphere have to be estimated accurately by the model for several reasons. Forecasting models, particularly those used for medium range forecasting, need good descriptions of boundary processes to allow synoptic-scale systems to be simulated faithfully throughout their lifetime, to simulate important large-scale forcings and to permit the use of direct model output for operational applications. Surface fluxes over tropical oceans are also crucial for simulating the general circulation of the atmosphere and their anomalies. But also for climate studies, it is essential to be able to simulate accurately the surface fluxes in the model.

For oceanic models the exchange between ocean and atmosphere is the main external forcing. The most promising approach for obtaining estimates of surface flux values on a global scale on a daily basis for driving ocean models is to extract them from operational numerical prediction models of the atmosphere whose capacities in terms of assimilating observations of many diverse kinds and quality have reached a high level of development.

In the absence of measurements of surface fluxes suitable for validation the first step in assessing the accuracy of surface fluxes is to compare estimates obtained by state-of-the-art global prediction models and climatological estimates.

2. DATA

Climatological data sets used in this study are those by Jaeger (1976) for precipitation, Mintz and Serafini (1989) for evaporation over land, Oberhuber (1988) for evaporation over oceans and Han and Lee (1981) for surface stresses. Global averages of the energy and water cycle are compared with estimates by Ramanathan et al. (1989) as well as with those by Hoyt (1976). Climatological estimates differ considerably because of lack of data and because of uncertainties in model assumptions. Some aspects of these differences will be discussed below.

The operational centres that can provide surface flux estimates readily are ECMWF, the UK Meteorological Office (UKMO) and the National Meteorological Center, Washington (NMC). Their analysis/forecasting schemes differ considerably in design and formulation and are therefore a good choice for a comparison. The main differences are as follows:

a) The ECMWF and NMC models are formulated in spectral coefficients and the UKMO model in finite differences.

b) The important subgrid scale processes are estimated by parametrization schemes which have been independently developed in the three meteorological centres. Especially the convection and radiation schemes give notably different simulations in the tropics. The importance of these processes will also be demonstrated by comparing different versions of the ECMWF analysis/forecasting scheme.

c) ECMWF and NMC assimilate observations by the use of optimum interpolation techniques, albeit with different parameters, followed by non-linear normal mode initialization, while the UKMO system applies a repeated insertion of observations into a forecasting model over a period. The former approach provides smoother first guesses and allows therefore a tighter data checking, while the latter approach allows the analysis of small scale features.

d) The quality control procedures and the criteria for accepting and rejecting observation are notably different and can lead to crucially different analysis in some cases.

e) The flux data used in the comparisons from ECMWF are averages over a 24 hour forecast from initial data at 12 GMT (other forecast ranges are investigated as well), data from NMC are averages of the two forecasts at 00 and 12 GMT for the forecast range 6 to 12 hours and data from UKMO are averages of 12 hour forecasts at 00 and 12 GMT.

All these differences in the analysis/forecasting schemes can lead to substantial differences between data sets, especially over areas with low observational data density. There is a constant effort to improve the analysis/forecasting schemes and therefore they are updated from time to time. The Annex 1 gives an overview of important analysis/model changes since 1985 at ECMWF.

No attempt has been made to recalculate diabatic forcings from analyses by which a separation of effects from different processes might have been possible. Such an approach would suffer much more from inconsistencies between analysis data and the model formulation than the chosen approach. Such inconsistencies lead to adjustment processes in the early forecasts (spin-up). To reduce the impact of these problems the NMC data set excluded values of the first 6 hour forecasts.

These adjustment processes are partly due to errors or imperfections in the analysis schemes and partly due to model errors. Systematic model errors will influence the analysis adversely mainly in data sparse areas. There are numerous sources for systematic errors which can affect the surface fluxes in the short range forecasts, e.g. unrealistic boundary layer structures in the model which are inconsistent with observational data. In such cases the analysis/forecasting scheme can reject the observation, leading to a wrong analysis, or accept it which will lead to an adjustment back to the model structure in the early forecasts (spin-up).

There is no guarantee that estimates of surface fluxes are correct because all models or climatological estimates give similar results. For example, Reynolds et al. (1989) have shown that surface winds in different operational analyses agree reasonably well with each other for the tropical Pacific but a comparison with independent buoy observations was less favourable. This problem has to be kept in mind in the following discussion.

It will however be shown below that despite all these uncertainties and possibilities of differences between data sets of surface fluxes there are some clear signals which point to deficiencies of the analysis/forecasting scheme in some respects and to reassurances of its quality in others. The study will concentrate on the atmospheric water budget and on surface stresses. Mainly oceanic areas will be investigated and there the surface stresses can be restricted to the frictional (turbulent) stresses while over continents form drag and gravity wave drag would have to be considered as well.

3. GLOBAL MEANS OF DIABATIC FORCINGS

Illustrated in Fig. 1 are global and annual means of the energy and water cycle in the day 0-1 and day 9-10 forecasts of the ECMWF model for two years (May 88 - April 89 and May 89

- April 90) together with climatological estimates by Ramanathan et al. (1989). In these two years considerably different versions of the ECMWF model were in use. The main differences were the formulations of convection and radiation (see Annex 1). The climatological estimates by Ramanathan et al. (1989) are chosen here for comparison but estimates by others will be mentioned below as well. Ramanathan's estimates provide a stronger water cycle than others.

The climatological estimates are balanced by construction. In contrast the forecasts are unbalanced particularly in the day 0-1 forecasts because of adjustment processes (spin-up) between analysis data and model formulations. A large residual suggests low reliability in at least one of the components and this is taken up in the discussion below.

The latent heat fluxes in the day 0-1 forecasts are lower than they are for day 9-10 forecasts and lower than the climatological estimates and by implication are low when compared with precipitation amounts. Latent heat fluxes in short range forecasts by other forecasting centres are also higher as shown below. This "underestimation" is due in part to the inconsistent use of satellite data in the analysis and in part to the formulation of the model. First results from a recent model change (June 90, see Annex 1) show increased latent heat fluxes especially in the short range forecasts.

The day 9-10 forecast values are also lower than those from climatological estimates. For the year 1989/90 they are however within the uncertainty of climatological estimates, i.e. Hoyt (1976) gives values of 72 to 84 W/m^2 and Jaeger (1976) gives precipitation amounts from which evaporation values of 82 W/m^2 can be inferred. Recent model changes (May 90 and June 90) led to further increases of these fluxes and of precipitation. For the year 1988/89 the day 9-10 values are too low.

Solar radiation values suggest that for the more recent model (1989/90) the albedo of the earth/atmosphere is too low for both forecast ranges, especially for day 0-1, while the earlier model was more reasonable in this respect. In the more recent model too much solar radiation reaches the ground and warms it excessively. Too high surface temperatures lead to excessive thermal radiation and sensible heat fluxes. The effect on these latter processes are mainly obvious in the day 9-10 forecasts because it takes some time for the model to heat up the ground. The better global mean albedo in the earlier model is offset by a much worse geographical distribution of the albedo (Arpe, 1990). In the earlier model the absorption by the atmosphere was too large and the albedo was larger too (though more reasonable) than in the recent model and therefore the ground received too little energy. First results after the model change in May 90 (run-off) and in June 90 (convective clouds) show clear improvements in this respect, i.e. increased albedo, less insolation at the ground and less sensible heat and radiative fluxes from the ground in the order of 10 W/m^2.

It will be shown below that there is excessive tropical precipitation in the ECMWF short range forecasts (day 0-1) of the more recent model especially during JJA while day 1-2 forecast values were more realistic. In global and annual means as shown in Fig. 1 the differences between both forecast ranges are small because a decrease in convective precipitation from 67 to 62 W/m^2 is nearly compensated by an increase from 16 to 19 W/m^2 in the large scale precipitation. Total precipitation amounts of 80 to 83 W/m^2 are small compared to the estimates by Ramanathan et al. (1989) but agree with those by Jaeger (1976) and Hoyt (1975).

Our knowledge of precipitation amounts is especially uncertain for the oceanic areas of the tropics and the southern hemisphere. In recent years estimates from infrared measurements by satellite (NOAA/CAC, 1989) have become available for the tropics. In Fig. 2 zonal mean precipitation amounts from different sources are compared. In the tropics, there are more similarities between the model produced precipitation and the estimates from satellite than with Jaeger's climatological values. Precipitation in the model and estimates from satellite show a clear tropical double maximum with a relative minimum at the equator. Precipitation amounts at the northern tropical maximum exceeds the climatological values by more than 10%. At the southern tropical maximum only the estimates from satellite observations exceeds those of the climatology while model values are similar (day 0-1) or lower (day 9-10) than climatological values. On the whole this comparison suggests that Jaeger's climatology underestimates the tropical precipitation. This is also supported by larger global mean precipitation in the estimates by Ramanathan et al. (1989) - 90W/m^2 - compared to those by Jaeger (1975) - 82 W/m^2. However it will be shown below that satellite estimates and the short range forecast precipitations tend to provide too large precipitation amounts over tropical continents.

From Fig. 1 it is clear that the precipitation amounts in the day 9-10 forecasts are improved with the May 89 model change. First results from reducing the run-off of convective precipitation over continents and from increasing the evaporation over sea under low wind speed conditions (May and June 90) show some increases of precipitation of perhaps 5% (see Fig. 12).

For annual and global means the evaporation and precipitation should balance. In the day 0-1 forecasts large imbalances result from too low evaporations and this problem will be further studied in the next sections. After the May 90 and June 90 model change the balance has been considerably improved, mainly due to the increase of evaporation under low wind speed conditions over oceans.

4. GEOGRAPHICAL DISTRIBUTIONS OF EVAPORATION

In Fig. 3 geographical distributions of evaporation for the season June to August are illustrated. The top panel shows the climatological estimates over oceans calculated by Oberhuber (1988). These estimates have large uncertainties. One source of uncertainty comes from the availability of observations by ships. Where the data density is too low the map has been left blank. Further uncertainties result from the conversion between a Beaufort wind scale and wind speeds, a revised conversion table can increase the evaporation over the tropical Atlantic by 40 W/m^2 (Isemer and Hasse, 1990). In addition the transfer coefficient in the bulk formula for evaporation is not well known and ECMWF has recently increased it under low wind speed conditions part of which could also influence the climatological estimates. Despite these uncertainties some clear signals can be seen from Fig. 3.

The short range forecast made with the ECMWF model (the two central panels) have over large parts of the tropical and southern hemisphere oceans considerably lower levels of evaporation compared with the climatological estimates (upper panel). Differences of more than 40 W/m^2 are widespread. In Fig. 4 latent heat fluxes in short range forecasts from different models are compared. All three models provide patterns of evaporation which are similar in many respects but again the evaporation in the ECMWF model was lowest while the NMC model provided values which are comparable to the ones in the climatological estimates. The evaporation in the ECMWF model is low where the wind speeds are low and this problem was addressed by the June 90 model change. This increased the evaporation amounts in the short range forecasts generally to amounts similar to those in the Oberhuber climatology. ECMWF latent heat fluxes are still low compared to NMC over the Trade wind areas in connection with lower surface stresses. Latent heat fluxes in the ECMWF model are also low in areas of tropical precipitation and in this respect the ECMWF model could be more realistic because it accounts for evaporation from falling rain drops. For some selected areas the area mean evaporation from all three models on a daily scale are shown in Fig. 5. In spite of the biases the day by day variability of evaporation in all three models was highly correlated. This suggests that observational data have a strong impact on the latent heat fluxes in the short range forecasts of the models.

To illustrate the underlying source of the biases in the ECMWF short range forecasts, the differences between the day 9-10 forecast values and the climatological estimates are displayed in Fig. 3 (lowest panel). Differences are distributed as could be expected for an anomaly map with positive and negative areas balancing each other. Day 0-1 and day 9-10 values differ most where there are only few observational data and these differences in the evaporation result mainly from differences in the humidity at the lowest model level between both forecast ranges. Over large areas the analyses at 1000 mb are moister by 2 g/kg than the day 10 forecasts which is sufficient to explain the differences in the evaporation.

In the areas of large bias in the evaporation the main data sources are those from satellites. There are only few radiosonde stations in these area and these report often only during day time (see Fig. 6, lower panel). To show impacts of different data sources on the analysis, differences in humidity between 12 GMT and 00 GMT analyses are displayed in Fig. 6 (upper panel). The day-night differences are largest at positions of radiosonde stations which report only once a day, at 00 GMT over the Pacific and at 12 GMT over the Atlantic.

Positive differences over the Pacific and negative differences over the Atlantic suggest that radiosonde data lead to a reduction of humidity in the analysis or, probably the real problem, that satellite data lead to a moistening of the analysis. The source of these biases is not yet clear, since the humidity analysis is affected both by humidity observations and by the temperature. Experiments in which all satellite observations are neglected resulted in less moist analyses, larger latent heat fluxes in the short range forecasts and less spin-up. Eliminating satellite observations altogether is of course an unrealistic option and further work is needed in order to develop procedures to use satellite data more effectively over oceanic areas.

Following the June 90 model change the latent heat fluxes over tropical oceans have been increased in the day 0-1 forecasts and as a result anomaly maps now look more realistic. However the problem with the humidity analysis at the surface is still present. Without biases in the humidity analysis from satellite observations the evaporation in the short range forecasts would probably become larger than the climatological estimates as can be found for the day 9-10 forecasts.

Day-night differences of 1000 mb temperatures show also largest differences (about 0.5 K) at the positions of radiosonde stations with higher temperatures at day time. Such differences can be understood as radiosonde stations are placed on islands where the surface temperatures are higher during the day.

Mintz and Serafini (1989) have estimated the climatological means of continental evaporation. A visual comparison of May 89 to April 90 means of the model with these climatological means (Fig. 7) reveals similar distributions and amounts for most of the world. However there are some biases in the short as well as the medium range forecasts towards lower evaporation. Model values are particularly low over Africa south of 15°S and over Australia where the fluxes in the model are less than 0.5 mm/day while the climatological values are over considerable areas larger than 1.0 mm/day. Similar biases can be found over the deserts of the western United States. In these areas Mintz and Serafini (1989) have closely followed the precipitation estimates by Jaeger (Fig. 8) probably assuming the run-off to be small while in the ECMWF model there must be considerable run-off because the precipitation of the model in these areas agrees with Jaeger's climatology but not with the model's evaporation. The reduced run-off with convective precipitation which was introduced in the model in May 90, led to increases of latent heat fluxes over continents but the impact on the desert areas seems to be small.

There are also some areas with biases towards larger evaporation in the model compared to the climatological estimate, i.e. over Uruguay, southern China and Europe. The two former areas are those where the model produces also clearly larger precipitation than in Jaeger's climatology (see Fig. 8). It must be remembered that climatological estimates contain large uncertainties but are useful because they are often the only data available for validation. In fact most model changes in the past, which are generally introduced for physical reasons, resulted in changes towards the climatological estimates and likely towards more realistic conditions.

5. GEOGRAPHICAL DISTRIBUTION OF PRECIPITATION

In Fig. 8 annual mean precipitation in the model (May 89-April 90) as well as climatological estimates by Jaeger (1975) and estimates from satellite observations by Arkin (pers. comm.) are displayed. The latter becomes increasingly unreliable poleward of 20° in both hemispheres (Meisner and Arkin, 1987). The model precipitation appears to be noisier than the other estimates because of a shorter averaging period and because of a higher horizontal resolution. Generally there is a good agreement in the patterns as well as the precipitation amounts. Differences are discussed below.

Over tropical continents the short range forecasts agree with the satellite estimates, both providing larger amounts than Jaeger's climatology and the medium range forecasts. Probably the former overestimate the precipitation amounts.

The ITCZ over the eastern Pacific has a more equatorward position in Jaeger's climatology than in the other estimates. In this respect the estimates from satellite should be reliable. In this area the model provides probably unrealistically large amounts of precipitation. The annual mean gets its main contribution from the June to August season. It was expected from the June 90 model change that these precipitation amounts would be reduced but first results after its implementation do not show such an impact.

Over the Indonesian area the medium range forecasts have much less precipitation than the short range forecasts and in this respect the short range forecasts are more realistic. The June 90 model change resulted in larger precipitations in this area in both forecast ranges, more in the day 9-10 than in the day 0-1 forecasts but there is still a reduction during the course of the forecast. If data of a whole year with the present model would be available, then Jaeger's climatology would probably give the lowest estimates in this area.

A good example which demonstrates the spin-up problem of precipitation is the Indian subcontinent during summer. Fig. 9 shows precipitation estimates from different sources. The manual analysis by NOAA/USDA (1989), Jaeger's climatology and the model results agree in the patterns while the estimates from satellite observations (NOAA/CAC, 1989) look unrealistic over western India. Over large areas of north-eastern India in the day 0-1 forecasts the precipitation exceeds 600 mm/month. These unrealistically large values are a manifestation of the spin-up of the model. The day 1-2 forecasts agree best with the manual analysis and provide probably good estimates of the truth.

The day by day variability has been investigated only for few grid points, over Europe. Only grid points have been chosen for which several observational observing stations were available. Fig. 10 shows time series of precipitation for the grid point "Berlin" and "southern Switzerland" representative for flat and alpine orography respectively. For winter months the model is able to capture the day by day variability very well. During summer the correlation between observations and forecasts is much lower. In this season the precipitation over Europe is dominated by convection. The lower correlation is not necessarily only a manifestation of model problems with simulating convective precipitation but could also result from sampling problems in the observations as a denser data network is needed for convective than for frontal precipitation. Also day 1-2 forecasts have been compared with observations and it became obvious that day 0-1 precipitation forecasts are superior to the day 1-2 values.

6. INTERANNUAL VARIABILITY OF THE WATER CYCLE IN ECMWF FORECASTS

For selected areas the latent heat fluxes in the day 0-1 and day 9-10 forecasts of monthly means as well as in the climatological estimates have been averaged and time series are displayed in Fig. 11. Values from climatological estimates are repeated every year.

The May 1989 model change is marked by a steep increase of latent heat fluxes in the day 9-10 forecasts for the tropical oceans as well as for the mean over all oceans. The forecast values agree now with estimates by Oberhuber (1988). The day 0-1 forecasts show such a clear increase only for the tropical oceans and this is connected with an increase of surface wind speeds in the Trade wind areas. In addition, in the mean over all oceans and seas an increase of latent heat flux in the day 0-1 forecasts can be seen during 1989 which occurred some months after May. It is not clear if this increase which took place around October 1989 is due to the May 89 model change concealed by an annual cycle, or if corrections to the analysis scheme during August 89 could have caused it. The June 90 model change led to increases of latent heat fluxes in the day 0-1 forecasts to the same level as the climatological estimate by Oberhuber (1988).

For the average over all land grid points no climatological estimate was readily available and therefore only the two forecasts ranges are compared. The fact that both forecast ranges give nearly the same amounts of evaporation suggests that this quantity is not directly affected by observational data and that the model is the dominating factor. Increases with the May 90 model change are clearly indicated. The steep increases of precipitation over land with the May 89 model change (Fig. 12) are not accompanied by similar increases of evaporation.

Looking back at earlier model versions one finds that the underestimation of latent heat fluxes over ocean in the model was less severe before April 1987. In April 1987 the surface parametrization over continents was modified and the Charnock constant for oceanic areas was reduced. This model change led to a decrease of latent heat fluxes over continents, which can be seen in the panel for all land points and was expected to reduce the evaporation over oceans only slightly (Blondin and Böttger, 1987). The reason for the strong decrease in the day 0-1 forecasts at this time over the oceans is not understood. It should be pointed out that the decrease of latent heat flux over oceans with this model change is much less in the day 9-10 forecasts than in the day 0-1 forecasts.

Impacts from changes in the analysis-forecasting scheme on the latent heat fluxes in the northern hemisphere extra tropics are less strong than in the tropics. In the extra-tropics the interannual variability of the atmospheric circulation dominates the interannual variability of latent heat fluxes and for the day 0-1 forecasts they most likely reflect the true anomalies. As an example the latent heat fluxes of the northern subtropical Pacific are shown in Fig. 11 (lowest panel). The enhanced evaporation in the day 0-1 forecasts during the ENSO event 1986/87 is clearly marked. The day 9-10 forecasts did not capture this anomaly. They are more affected by the May 1989 model change than the day 0-1 forecasts. The ENSO event 1986/87 is also clearly reflected in the precipitation over the tropical Pacific (Fig. 12) in the day 0-1 forecasts but not in the day 9-10 forecasts.

It is worth mentioning in this context, that the insensitivity of the ECMWF model to SST anomalies (ENSO events) was a feature of the version of the operational model after May 85. Recent experiments by Palmer et al. (1990) with the June 90 model version show that the model is now significantly more responsive to SST anomalies.

The change of the spin-up during the 5 years of investigation can be seen from Fig. 11 and 12 by comparing day 0-1 with day 9-10. In the latent heat flux the spin-up is only a feature over oceans and seas. It only became large with the May 89 model change when the medium range evaporation amounts were increased to a level similar to the climatological estimates but not so far the evaporation in the short range forecasts. The June 90 model change also increased the day 0-1 forecast values to the same level as the day 9-10 forecasts or the climatology. One would have expected that the June 90 model change would have had impacts on the day 9-10 forecasts as well and initial results after the introduction of this model change did suggest such an increase also for the day 9-10 forecasts but this is not evident in Fig. 11.

The spin-up in the precipitation has always been a feature of the analysis/forecast with larger precipitation amounts in the short range forecasts. A major change in its characteristics occurred with the May 89 model change after which the maximum of precipitation occurred in the very early part of the forecasts whilst before the maximum occurred between day 1 and 2. From Fig. 12 it can be seen that at this time the changes of the spin-up were even stronger when separating between continents and oceans. Over oceans the spin-up disappeared and precipitation amount became similar to those by the Jaeger climatology while the spin-up was enhanced over continents. This enhancement was especially large in the tropics in connection with convective precipitation and steep mountains.

For the period December 89 to May 90 the precipitation in the day 0-1 forecasts over oceans is lower than the day 9-10 values by 10 W/m^2. The decrease has to be assigned to a change in the analysis scheme during November 89, when a tighter data control for SATOB data was introduced. This data checking influenced mainly data between 20°N and 30°N over both oceans and there the impact is felt in the precipitation. The enhancement of evaporation under low wind speed conditions (June 90) led to increases of precipitation in the day 0-1 again to levels similar to Jaeger's climatology and the day 9-10 forecasts.

The latent heat flux and precipitation zonally averaged over land points for the European-African area in the day 0-1 forecasts are displayed in Fig. 13 as a latitude-time cross-section. For Europe the maximum evaporation during late spring have been increased strongly with the April 87 model change, slightly during May 89 and again during May 90. The latter increases go hand in hand with an increase of precipitation in the day 0-1 forecasts.

The Sahel zone is in Fig. 13 clearly indicated by a belt with latent heat fluxes and precipitation below 10 W/m^2. This belt is widening during the April 87 model change. At this model change the evaporation in the tropics was considerably reduced not only in their maximum amounts but also by a shift of the boundary between low values in the Sahel zone and tropical maximum by 2°-5° equatorwards in both hemispheres. Increased evaporation in the Sahel zone for a few months after the April 87 model change is not understood. There is a marked increased of precipitation in the Sahel zone with the January 89 analysis change; this is mainly due to coastal precipitation.

The May 89 model change, which brought a good increase of evaporation over tropical oceans (see Fig. 11), did not result in increases of latent heat fluxes over tropical continents. This was unexpected because the precipitation amounts over tropical continents were increased considerably by this model change, e.g. for August over Africa the precipitation maxima increased from 250 W/m^2 to 420 W/m^2. The increase of precipitation over central Africa must therefore have resulted from increased humidity fluxes from the oceans and the increased precipitation reaching the ground is not available for evaporation but for run-off.

A reduction in the run-off of convective precipitation (May 90) resulted in an enhancement of evaporation over Central Africa in the short as well as in the medium range forecasts. Also the belt of low evaporation in the Sahel zone was reduced by this model change, exhibited mainly by a poleward shift of its equatorial boundary.

The evaporation over Africa displays clear annual cycles with maxima in the southern hemisphere around March and in the northern hemisphere around October, i.e. at the end of the rainy season. However, this pattern has been disturbed during 1989/90 because of unintentional maintenance of the deep soil climatological values to those for August. The re-installation of the annual cycle of these quantities during April 90 restored the cyclic in these contours. Also the latent heat flux over Europe shows impacts from this error.

The day 9-10 forecast values (not shown) have similar characteristics as those of the day 0-1 forecast except that the values are slightly lower and the impacts from changes in the analysis/forecasting scheme are less strong.

7. SURFACE STRESSES - GEOGRAPHICAL DISTRIBUTION

In Fig. 14 the surface stress in the ECMWF model, for the season June to August 1989, are compared with the climatological estimates made by Han and Lee (1981). The forecast values are generally lower than the climatological estimate. Differences of more than 0.05 N/m^2 (which is up to 50% of the climatological values) are widespread in the Trades. Very large differences (up to 0.3 N/m^2) can be found over the Indian monsoon area. These differences can be due to anomalies of the atmospheric circulation, to biases in the climatological estimates or to biases in the model. Biases in the climatology or the model can result from a low observation density over tropical areas. Some reasons for the large differences are discussed below. Differences from climatological estimates are generally larger in the day 0-1 forecasts than the day 9-10 forecasts except over the Indian monsoon area and over the tropical Pacific off Central America.

Arpe et al. (1988) compared surface stress fields derived from short range forecasts made by ECMWF, UKMO and NMC models. Fig. 15 shows the surface stress fields of the three models for the period 1 June to 27 July 1988. For comparison also the June/July climatology by Han and Lee (1981) is presented. Similarities between the models as well as with the climatology are obvious. The agreement between the models is especially good in northern hemisphere mid-latitudes. This is further demonstrated in Fig. 16 showing day by day values of surface stresses for selected areas by the three models. As with latent heat flux shown above one can assume that the variability in the surface stress is due to observational data and is therefore most likely to be realistic. In the Trades (Fig. 15) there is a clear bias of the ECMWF stresses towards lower values. The NMC values are the highest of the model stresses but they are still slightly lower than the climatological estimates. Despite these biases the day by day variability is very similar between all three models (Fig. 16). For the Indian monsoon area all three models give stresses which are much more similar to each other than to the climatological values. These problem areas will be further discussed below.

Since this comparison there has been a major modification of the ECMWF model which took place on 2 May 1989 (see Annex 1). For the period 19 April to 1 May 1989 the pre- and post 2 May 90 versions of the ECMWF model were run in parallel. In addition surface stresses from short range forecasts at NMC were also available and in Fig. 17 the stresses from the three models are compared. The more recent ECMWF model provides clearly stronger stresses than the older one. For the Pacific the values by the more recent model are nearer to those produced by the NMC model but are still somewhat lower, whereas for the Atlantic they are larger.

A further major model change introduced in June 1990 (see Annex 1) also appears to have increased the surface stresses in the Trades further but are still smaller than the climatological estimates by Han and Lee (1981).

8. INTERANNUAL VARIABILITY OF SURFACE STRESSES

Arpe and Esbensen (1989) investigated the interannual variability of monthly mean surface stresses. Some of the variability seemed to be realistic e.g. in connection with the ENSO event 1986/87. This is illustrated in Fig. 18 and 19 which show time series for day 0-1 and 9-10 forecasts and climatology. In the northern extra tropics monthly means of the day 0-1 and day 9-10 forecast values agree reasonably well with climatological estimates. Deviations seem to be due to anomalies in the atmosphere, e.g. the larger stresses over the Pacific 30°-60°N during the ENSO event 1986/87 and over the Atlantic 30°-60°N during the winter 89/90 when the North American trough was shifted eastwards and many strong storms reached the British Isles. Both events were captured by the short as well as the medium range forecasts.

The main event in the tropics (10°N - 10°S in all three oceans) corresponds to an increase of surface stresses around May 1989 in the day 0-1 and day 9-10 forecasts by more than 0.01 N/m^2. This however is most likely due to the model change at that time. The impact on the day 9-10 forecasts is generally larger than on the day 0-1 forecasts.

Impacts from the ENSO event 1986/1987 can be seen in the tropical Pacific by relatively low stresses in the day 0-1 forecasts. These low surface stresses agree with wind speed minima during ENSO events shown by Halpert and Ropelewski (1989). This impact is not reflected in the day 9-10 forecasts.

Fig. 19 (top panel) shows a time series of surface stresses over the North Arabian Sea. Dominant features are maxima during summer. Climatological estimates are nearly twice as large as the stress in the day 0-1 forecasts and day 9-10 values are even smaller than that. Above it has been shown that different models were very similar in this respect.

9. DIFFERENCES BETWEEN MODEL AND CLIMATOLOGICAL ESTIMATES OF STRESSES IN SELECTED AREAS

9.1 Indian Summer Monsoon

It has been shown above that the surface stresses over the North Arabian Sea during June to August are nearly twice as large in the climatological estimate as they are in the short range forecasts of different models and in different years.

To find out why the models produce so much lower surface stresses than the climatological estimate, a comparison of surface wind speeds (the main quantity to calculate the surface stresses) in the model with observations has been carried out. The only observations available in the Somali Basin/North Arabian Sea are those by ships of opportunity. For the area 52°-65°E, 0°-15°N during June 1989 129 ship observations have been used for the 12 GMT analysis and during June 90 there were 135 ship observations. Table 1 gives an overview over the mean surface winds at ship positions as observed and as analysed.

Table 1
Mean surface wind speeds and directions at positions of ship observations for 12 GMT during June 1989/June 1990

	OBS	FGS	ANA	INI
ff	12.7/12.2	10.2/10.8	11.7/11.7	11.5/11.3
dd	224/223	223/227	225/225	222/222

The observed wind speeds are markedly larger than those in the first guess (FGS) but also larger than in the analysis (ANA). The analysis scheme clearly accepted the observations and increased the wind speeds from the low first guess values toward the observed values. The initialization (INI) reduced the wind speeds again but only slightly. In a given boundary layer formulation the observed wind speed would produce markedly higher stresses than the first guess winds.

Hollingsworth (pers. comm., SAC(88)5) has shown for the extra-tropics that the model has difficulties to simulate vertical wind shears in the boundary layer which deviate strongly from a typical Ekman spiral. It is not clear if there is a connection but the areas with large biases in the surfaces stresses coincide with areas in which the vertical wind shear deviates strongly from an Ekman spiral. Over the Somali Basin there is a low level jet and from Table 1 it is suggested that the model reduces its strength. This cannot be verified for this area because there are no radiosonde stations available but below it will be shown for the Trade wind areas that the model tends in the 6 hour forecast for the first guess to reduce low level wind maxima.

Comparing in Fig. 14 the stresses in the day 0-1 with those in the day 9-10 forecasts reveals a further decrease of stresses with increases in forecast length. It has already been shown that during the course of the forecast there is a decrease of precipitation over India. One can expect with such a decrease of precipitation a decrease of convergent low level wind - the Indian monsoon circulation. Therefore the decreased surface stresses in this area is less a direct problem of the boundary layer parametrization but due to a change in the large scale circulation.

9.2 The tropical Pacific off Central America

Over the tropical Pacific Ocean off Central America in the northern hemisphere an onshore component of surfaces stresses in the model can be seen in Fig. 14. This increases with forecast length. Neither the climatological estimate nor the older version of the ECMWF model (Fig. 15) showed such a surface stress. Only the UKMO model had some indications in the June-July 1988 comparison (Fig. 15). In the present model it is not to be seen during the December-February season.

Over Central America and the adjoining ITCZ over the Pacific there is excessive precipitation (see above) and this could be accompanied by a spurious monsoon type circulation. Some positive impacts from the recent increase of evaporation at low wind speeds over oceans on this problem were expected but the results available to date are not yet conclusive. With the introduction of this model change the onshore stress component seems to be reduced in the short range forecasts but not in the medium range forecasts. Its impact on precipitation in this area is even less clear.

9.3 Trade winds

Over the Pacific ENE of Hawaii the differences between day 0-1 forecasts and the climatological estimates are quite large, up to 0.07 N/m^2 in Fig. 14.

A comparison between observational wind data and corresponding values in the analyses has also been carried out; again for June 1989 and June 1990.

From Table 2 a decrease of wind speeds with height between surface and 900 mb can be seen. As in the Indian monsoon area the model is not able to maintain or create this wind shear. The analysis scheme corrects the winds but the initialization reduces the surface wind speed again. Some of the observed vertical wind shear shown here may result from differences in the location between SATOB and SHIP observations but this effect is thought to be small. It should be noted that only wind observations which passed all checking procedures of the analysis scheme are used for this statistics.

Table 2
Mean wind speeds and directions over the area 15°-28°N, 130°-152°W in ship and cloud drift winds by satellite observations together with corresponding values during the analysis cycle for June 1989/June 1990 12 GMT

		OBS	FGS	ANA	INI
900 mb	ff	5.0/7.2	5.2/8.1	5.1/7.3	4.9/7.4
	dd	61/70	66/68	63/69	63/68
surface	ff	6.8/8.6	5.4/8.0	6.1/8.4	5.9/8.4
	dd	56/54	63/62	58/58	59/58

Ideally one would prefer to carry out such comparisons with radiosonde observations but there are none suitably positioned. The station which seems to be best for such a comparison is Ascension Island (8°S, 14°W). In the vicinity of this station there are also large differences between surface stresses in the model and climatology (Fig. 14). Table 3 gives an overview on the winds for this station.

As in other areas with large differences in the surface stresses between model and climatology, one finds a decrease of wind speeds with height. The first guess has much less of a vertical gradient. The analysis has been corrected towards the observations and the initialization reduces the surface winds towards those of the first guess. In this case both levels are affected by the analysis scheme.

Table 3
Wind speeds and directions for the radiosonde station 61902 (Ascension Island, 8°S, 14°W) during June 1989/June 1990 for 12 GMT.

		OBS	FGS	ANA	INI
850 mb	ff	4.0/4.7	6.1/6.3	4.9/5.9	4.4/5.1
	dd	106/107	112/110	110/108	111/109
1000 mb	ff	10.0/9.9	8.3/8.7	9.0/9.7	8.4/8.9
	dd	106/113	121/121	111/113	112/115

10. CONCLUSION

10.1 The atmospheric water cycle

The study has shown that the model's estimate of latent heat fluxes and precipitation are qualitatively reasonable. Latent heat fluxes over oceans and precipitation over continents in the short range forecasts over the northern hemisphere extra-tropics are probably good estimates of the truth. This has not only been found for monthly means but also for the day to day variability. This statement can probably be extended for precipitation over oceans.

Latent heat fluxes and precipitation in the tropics suffer from adjustment processes between analysis and model formulation (spin-up). For precipitation this problem is now largest over the continents. When using short range forecasts as estimates of the truth one should exclude the first 6 or 12 hours. The day 1 to 2 forecast of precipitation is probably a better estimate of the truth over tropical continents than estimates from satellite measurements. For latent heat fluxes the spin-up is restricted to oceanic areas and is especially large where the main observational data sources are satellites. Recently this problem has been reduced considerably.

The interannual variability of precipitation and latent heat flux in the short range forecasts often represent anomalies in the atmospheric circulation but changes in the analysis/forecasting scheme may have even larger effects, especially in the tropics and subtropics. Changes in the analysis/forecasting schemes in the ECMWF operational model have been introduced mainly for physical reasons. The fact that this led to changes of the atmospheric water cycle towards climatological estimates gives confidence in these estimates.

10.2 Surface stresses

Surface stresses in the ECMWF model, in other models and in climatological estimates are qualitatively similar especially in the northern extra tropics where there is a good observational data coverage. A high correlation betwee surface stresses in different short range forecasts in the day by day time scale suggests that the variability of the stress is caused by observational data and is therefore realistic. In the northern hemisphere mid-latitudes over oceans the ECMWF day 0-1 forecast stresses are probably a good estimate of the truth.

In the Trade wind areas the models provide less stress than the climatological estimates. For these areas the differences between the ECMWF short range forecasts and the climatological estimates have been reduced in recent years due to several model changes; notably the introduction of a mass-flux convection scheme together with a new radiation scheme in May 1989 was important in this respect. After this model change the ECMWF short range forecast stresses have become similar to those produced in the NMC model. Surface stresses in the Indian summer monsoon area by different forecast models are very similar to each other but reach only half the values of the climatological estimates.

Deviations between model data and climatological estimates are large where there is a low level wind maximum and where the vertical wind shear in the boundary layer deviates strongly from a typical Ekman spiral. The model seems to be unable to create or maintain such abnormal wind shears. This problem seems to be similar in other models.

Interannual variabilities of surface stresses in the short range forecasts reflect partly anomalies of the atmospheric circulation but especially for the tropics and subtropics the impacts from changes in the analysis/forecasting scheme can exceed those by natural variability.

References

Arpe, K., 1990: Impacts of changes in the ECMWF analysis-forecasting scheme on the systematic error of the model. ECMWF seminar on 10 years of medium-range weather forecasting, 4-9 September 1989.

Arpe, K., D. Burridge and A. Gilchrist, 1988: A comparison of surface stresses and latent heat fluxes over oceans in short range forecasts by ECMWF, UKMO and NMC. Proceedings of the 13th Annual Climate Diagnostic Workshop, 31 October - 4 November, 1988, 389-397.

Arpe, K. and S.K. Esbensen, 1989: Surface stresses and latent heat fluxes over oceans in short range forecasts: their annual and interannual variability and comparison with climatological estimates. Annalen der Meteorologie, 26, 128-130.

Beljaars, A. and M. Miller, 1990: A note concerning the evaporation from the tropical oceans sensitivity of the ECMWF model to the transfer coefficient of moisture at low wind speeds. ECMWF Tech. Memo. No. 170.

Blondin, C. and H. Böttger, 1987: The surface and sub-surface parameterisation scheme in the ECMWF forecasting system. ECMWF Research Dept. Tech. Memo. No. 135, 48 pp.

Halpert, M.S. and C.F. Ropelewski, 1989: Atlas of tropical sea surface temperature and surface winds. NOAA Atlas NO. 8, Silver Spring MD.

Han, Y.-J. and S.-W. Lee, 1981: A new analysis of monthly mean wind stresses over the global ocean. Climate Research Institute Report No. 26, Oregon State University, Corvallis, Oregon 97331, 148 p.

Hoyt, D.V., 1976: The radiation and energy budgets of the Earth using both ground-based and satellite-derived values of total cloud cover. NOAA Tech. Report ERL 362-ARL4. U.S. Dept. of Commerce, Washington, D.C., 124 pp.

Illari, L., 1989: The quality of satellite PWC data and their impact on analyzed moisture fields. Tellus, 41A, 319-337.

Isemer, H.-J. and L. Hasse, 1990: The scientific Beaufort equivalent scale: effects on wind statistics and climatological air-sea flux estimates in the North Atlantic Ocean. To be published.

Jaeger, L., 1976: Monatskarten des Niederschlags für die Ganze Erde. Berichte des Deutschen Wetterdienstes, 139 (Band 18).

Kelly, G. and J. Pailleux, 1988: Use of satellite vertical sounder data in the ECMWF analysis system. ECMWF Research Dept. Tech. Memo. No. 143, 46 pp.

Lönnberg, P., J. Pailleux and A. Hollingsworth, 1986: The new analysis system. ECMWF Research Dept. Tech. Memo. NO. 125, 21p.

Meisner, B.N. and P.A. Arkin, 1987: Spatial and annual variations in the diurnal cycle of large-scale tropical convective cloudiness and precipitation. Mon.Wea.Rev., 115, 2009-2032.

Miller, M., 1988: The sensitivity of systematic errors of the ECMWF global forecast model to parameterized processes. Workshop on Systematic Errors in Models of the Atmosphere, 19-23 Sept. 1988, Toronto, Canada, 289-296.

Miller, M. and T. Palmer, 1987: Orographic gravity-wave drag: its parametrization and influence in general circulation and numerical weather prediction models. ECMWF Seminar on Observation, Theory and Modelling of Orographic Effects, 15-19 September 1986, Vol. I., 283-333.

Mintz, Y. and Y.V. Serafini, 1989: Global monthly climatology of soil moisture and water balance. Note Interne LMD No. 148, Ecole Poltechnique, Palaiseau.

Morcrette, J.-J., 1990: Impact of changes to the radiation transfer parametrizations plus cloud optical properties in the ECMWF model. Mon.Wea.Rev., 118, 847-873.

NOAA/CAC, 1989: Climatological Diagnostic Bulletin, August 1989. Available from NOAA/National Weather Service, National Meteorological Centre, Climate Analysis Centre, Washington D.C., USA.

NOAA/USDA, 1989: Weekly Weather and Crop Bulletin, August 1989. Available from NOAA/National Service.

Oberhuber, J.M., 1988: An Atlas based on the 'COADS' data set: the budget of heat, buoyancy and turbulent kinetic energy at the surface of the global ocean. Max-Planck-Institute for Meteorology Report No. 15. Max-Planck-Instut für Meteorologie, Hamburg 13, Germany.

Palmer, T.N., C. Brankovic and P. Viterbo, 1990: Month to seasonal prediction of the summer monsoon using NWP models with prescribed SST. Proceedings of the TOGA International Scientific Conference, Honolulu.

Ramanathan, V., B.R. Bartkstrom and E.F. Harrison, 1989: Climate and the Earth's Radiation Budget. Physics Today, American Institute of Physics, 22-32.

Reynolds, R.W., K. Arpe, C. Gordon, S.P. Hayes, A. Leetmaa and M.J. McPhaden, 1989: A comparison of tropical Pacific surface wind analysis. Jour. of Climate, 2, 105-111.

Shaw, D.B., P. Lönnberg, A. Hollingswroth and P. Undén, 1987: Data assimilation: The 1984/85 revisions of the ECMWF mass and wind analysis. Quart.J.Roy.Meteor.Soc., 113, 533-566.

Simmons, A.J., D.M. Burridge, M. Jarraud, C. Girard and W. Wergen, 1989: The ECMWF Medium-Range Prediction Models, Development of the Numerical Formulations and the Impact of increased Resolution. Met. and Atmos. Physics, 40, 28-60.

Slingo, J.M., 1987: The development and verification of a cloud prediction model for the ECMWF model. Quart.J.R.Met.Soc., 113, 899-927.

Tiedtke, M., 1989: A comprehensive massflux scheme for cumulus parametrization in large-scale models. Mon.Wea.Rev., 117, 1777-1798.

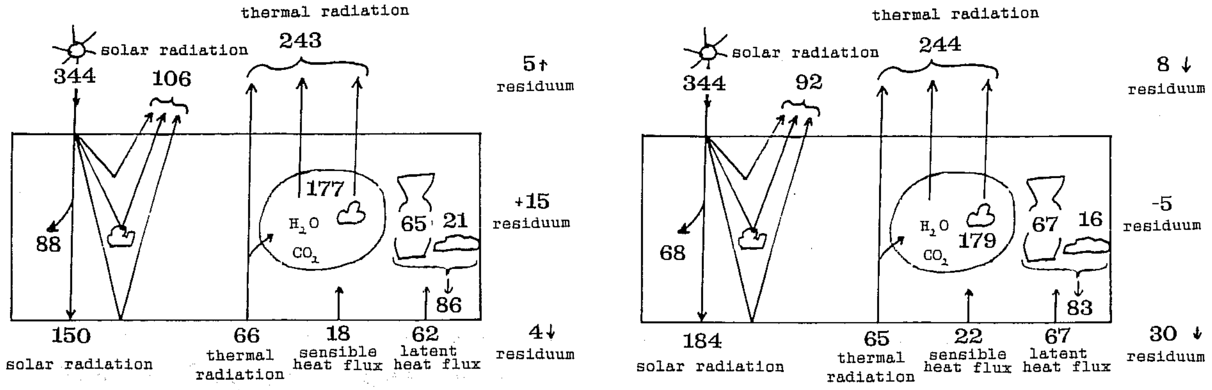
Tiedtke, M., W.A. Heckley and J. Slingo, 1988: Tropical forecasting at ECMWF: On the influences of physical parameterisation on the mean structure of forecasts and analyses. Quart.J.R.Met.Soc., 114, 639-664.

Undén, P., 1989: Tropical data assimilation and analysis of divergence. Mon.Wea.Rev., 117, 2495-2517.

Wergen, W., 1989: Normal mode initialization and atmospheric tides. Quart.J.R.Met.Soc., 115, 535-545.

Annex 1
Important changes in the analysis-forecast scheme

May 1985	The new T106 model became operational together with the introduction of a shallow convection scheme, modified Kuo-scheme and new representation of cloudiness (Tiedtke et al. 1988; Simmons et al. 1989; Slingo, 1987).
March 1986	Tides are handled by initialization (Wergen, 1989).
March 1986	Use of satellite precipitable water content data and modified (reduced) use of SYNOP data in humidity analysis (Illari, 1989).
May 1986	Model levels were increased to 19 (Simmons et al. 1989).
July 1986	Gravity wave drag parametrization was introduced (Miller and Palmer, 1987).
September 1986	The analysis scheme was modified (Lönnberg et al., 1986).
November 1986 - March 1987	Problems with temperature observations from satellite.
April 1987	The parametrization of surface processes was revised (Blondin and Böttger, 1987).
July 1987	The analysis uses only 7 instead of 11 layers of SATEM data (Kelly and Pailleux, 1988).
December 1987	A tighter quality control of cloud drift winds in the analysis was introduced.
January 1988	Vertical diffusion scheme above PBL was removed (Miller, 1988).
January 1988	Analysis of divergent wind improved (Undén, 1989).
July 1988	Analysis of small scales improved.
September 1988	New method of satellite retrievals by NOAA/NESDIS.
November 1988	Change to initialization.
January 1989	Reduced impact of satellite humidity on analysis.
May 1989	Replacement of the radiation scheme (Morcrette, 1990) replacement of Kuo convection by a mass-flux scheme (Tiedtke, 1989), revised gravity wave drag.
August 1989	Remove spurious low level temperature increments in the analysis scheme.
September 1989 - April 1990	Deep soil climatology fixed to August values.
November 1989	Tighten SATOB quality control.
May 1990	Reduced run-off of convective rain, modified convective cloud scheme and revised pressure gradient term.
June 1990	Increased evaporation at low wind speeds over sea, (Beljaars and Miller, 1990), parametrization of non-precipitating clouds.

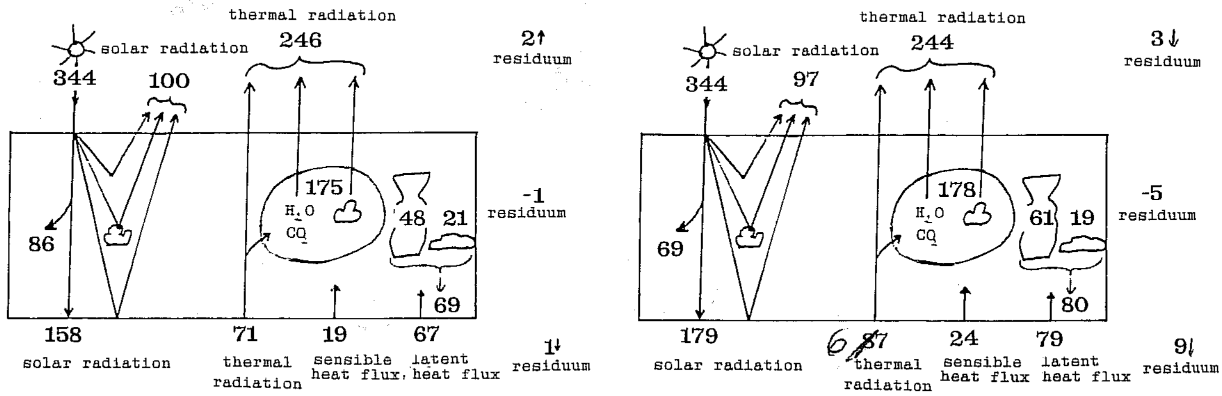


day 0-1
May 88-April 89

residuum water 24↓

ECMWF day 0-1
May 89 - April 90

16↓
residuum water

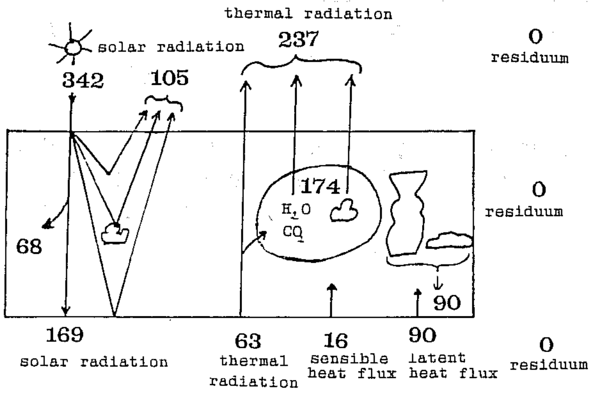


day 9-10
May 88-April 89

residuum water 2

ECMWF day 9-10
May 89 - April 90

1↓
residuum water



climate estimate 1989

Fig. 1 Global annual mean energy and water cycle derived from day 0-1 (upper panels) and day 9-10 forecasts (middle panels) and climatological estimates of these cycles by Ramanathan et al. (1989) (lowest panel). Model data from two years with different parametrization schemes are compared. Units: W/m².

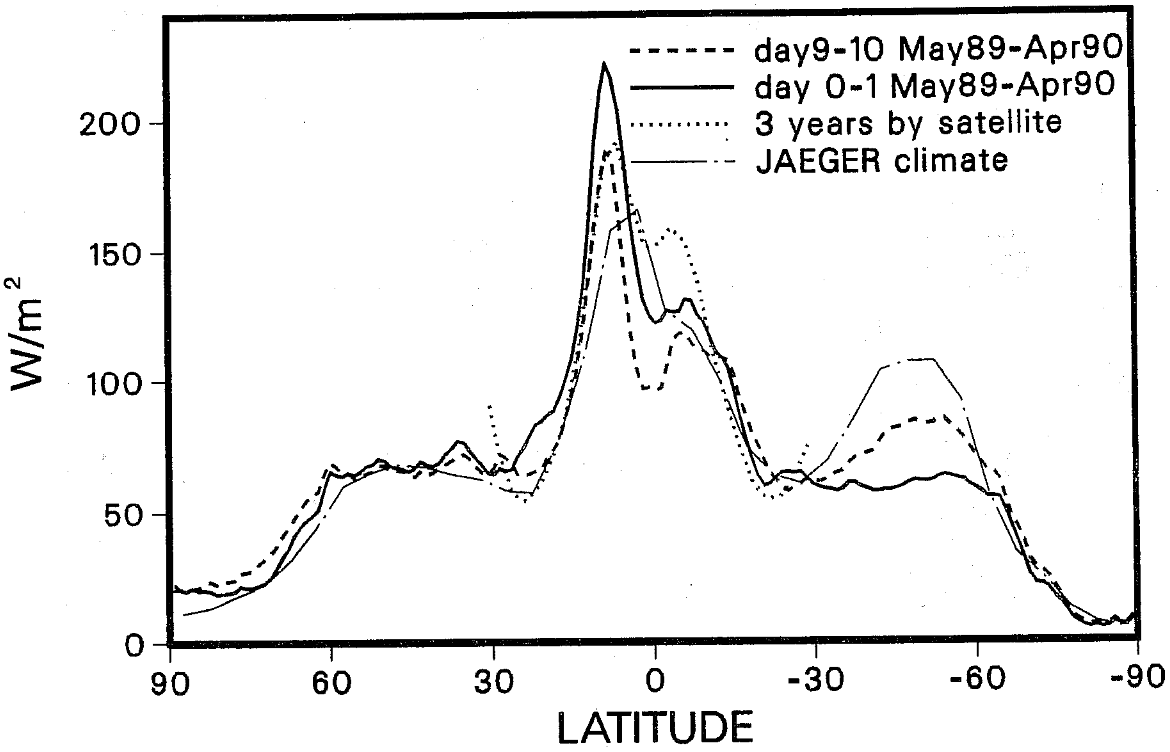


Fig. 2 Zonal and annual means of precipitation. Climatological estimates by Jaeger (1976) are compared with estimates from satellite measurements over 3 years (Arkin, Pers. Comm.) and with ECMWF day 0-1 and day 9-10 forecasts during May 89 to April 90.

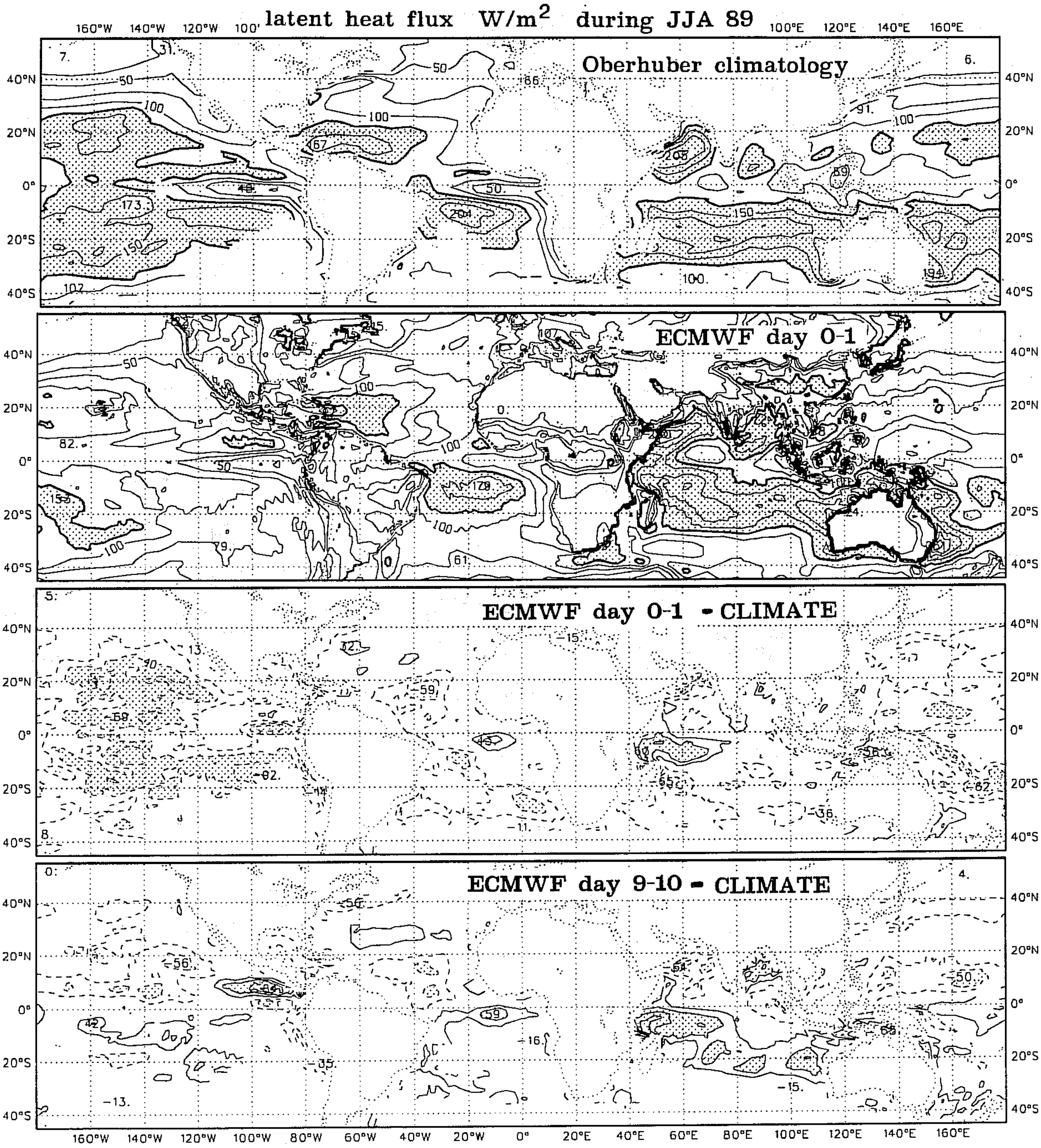


Fig. 3 Latent heat fluxes for the season June to August.
(a) Climatological estimate by Oberhuber (1988)
(b) ECMWF day 0-1 forecasts during 1989
(c) Difference between day 0-1 forecasts and the climatological estimate
(d) Difference between day 9-10 forecasts and the climatological estimate.
Contour interval: (a) and (b) 25 W/m², (c) and (d) 20 W/m².
Shading: (a) and (b) > 125 W/m², (c) and (d) > 40 W/m² or < -40 W/m².

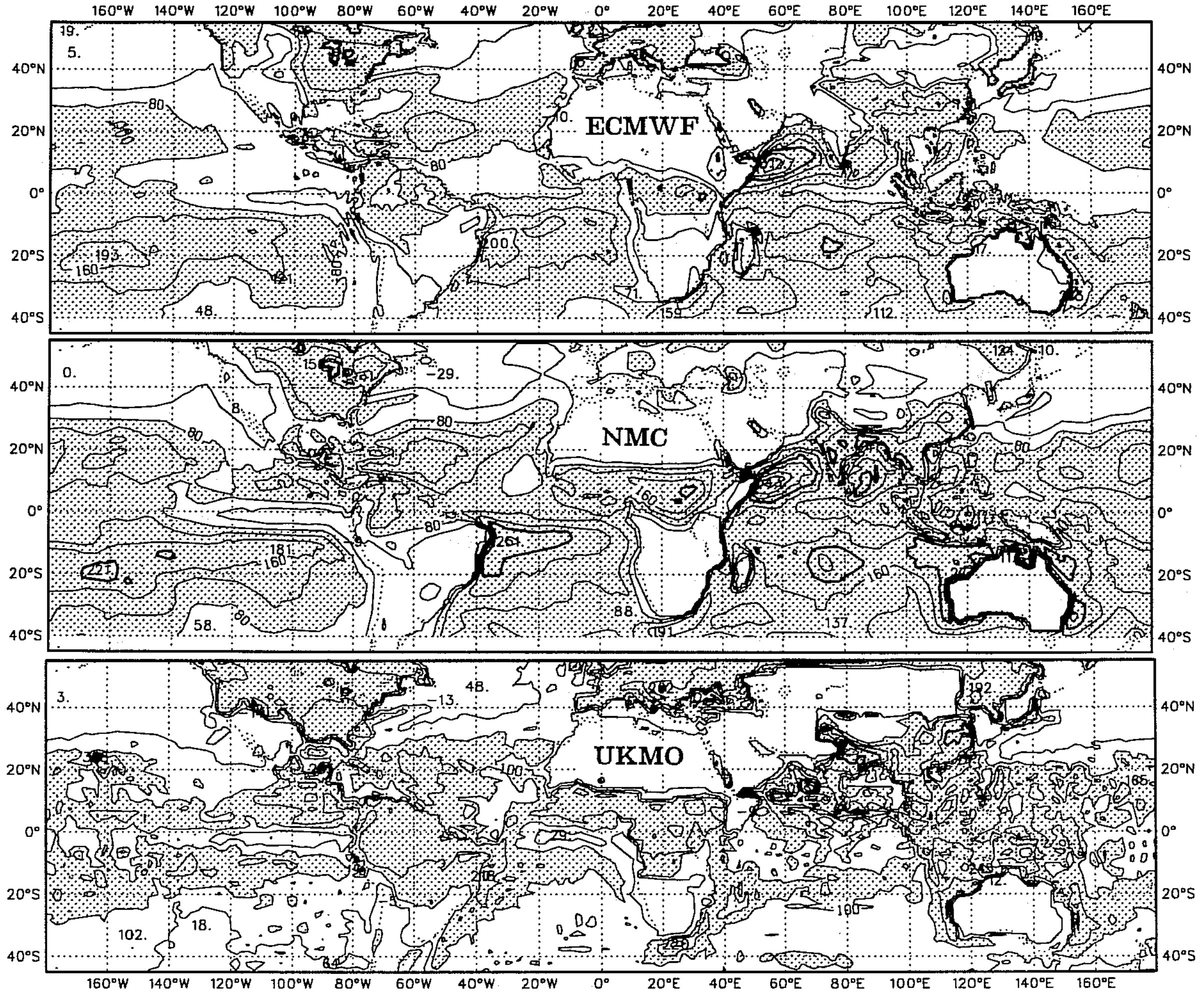


Fig. 4 Latent heat fluxes in the short range forecasts by ECMWF, NMC and UKMO averaged over the period 1 June to 27 July 1988. Contour interval: 40 W/m². Shading for more than 80 W/m².

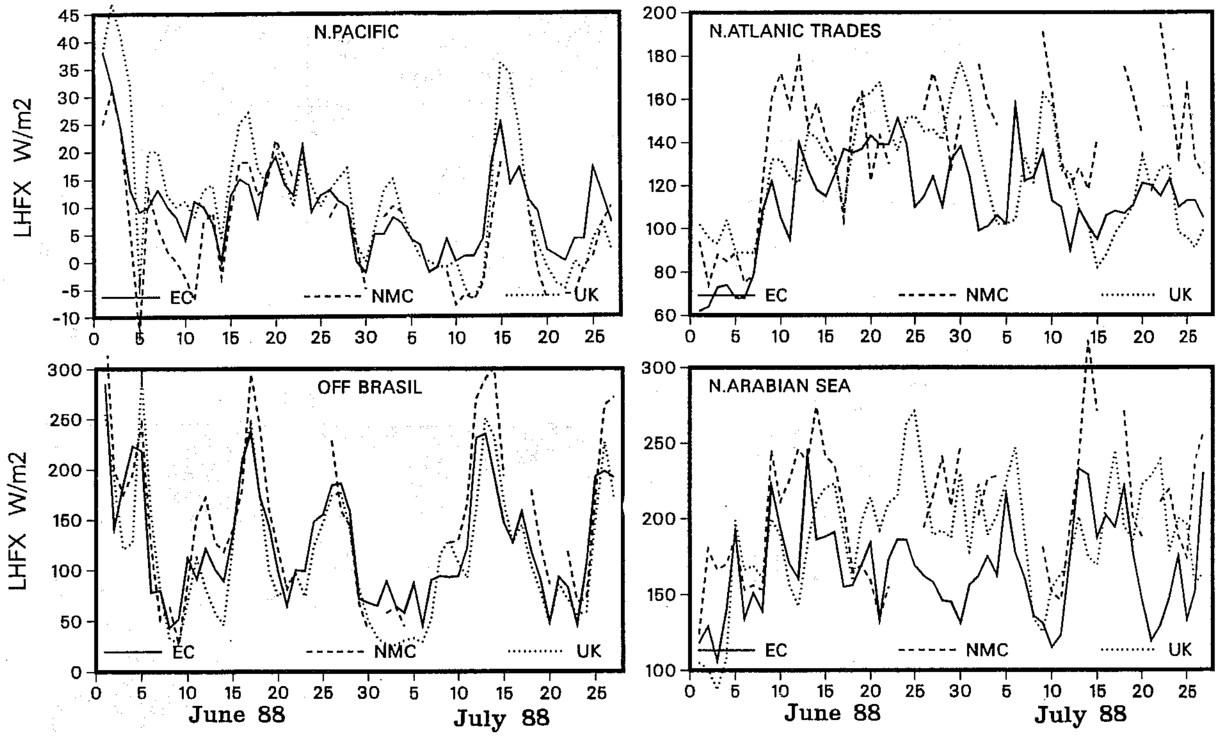


Fig. 5 Daily latent heat fluxes for selected areas in operational short range forecasts by ECMWF, UKMO and NMC for the period 1 June to 27 July 1988.

N. Pacific	37° - 46°N, 158°E - 174°W
N. Atlantic Trades	15° - 25°N, 33° - 50°W
N. Arabian Sea	11° - 22°N, 62° - 71°E
Off Brazil	23° - 30°S, 30° - 48°N

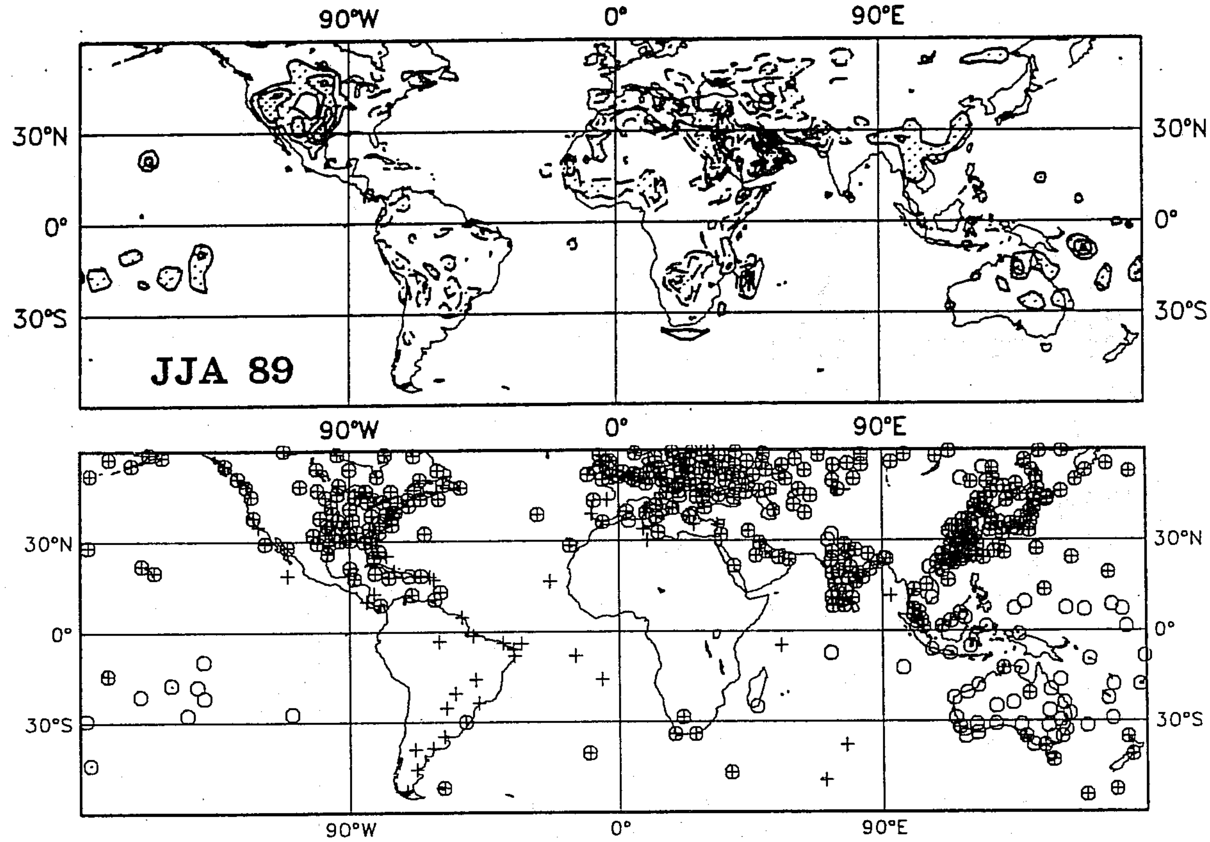


Fig. 6 Top panel: mixing ratio differences between 12 GMT and 00 GMT analyses at 1000 mb during JJA 89.
Contour interval: 1 g/kg. Positive if 12 GMT humidity is larger than 00 GMT humidity.
Lower panel: Distribution of radiosonde stations during June 89. Stations with less than 10 observations in that month are considered to be missing. Symbols used:
O = observations at 00 GMT only
+ = observations at 12 GMT only
⊕ = observations at 00 and 12 GMT

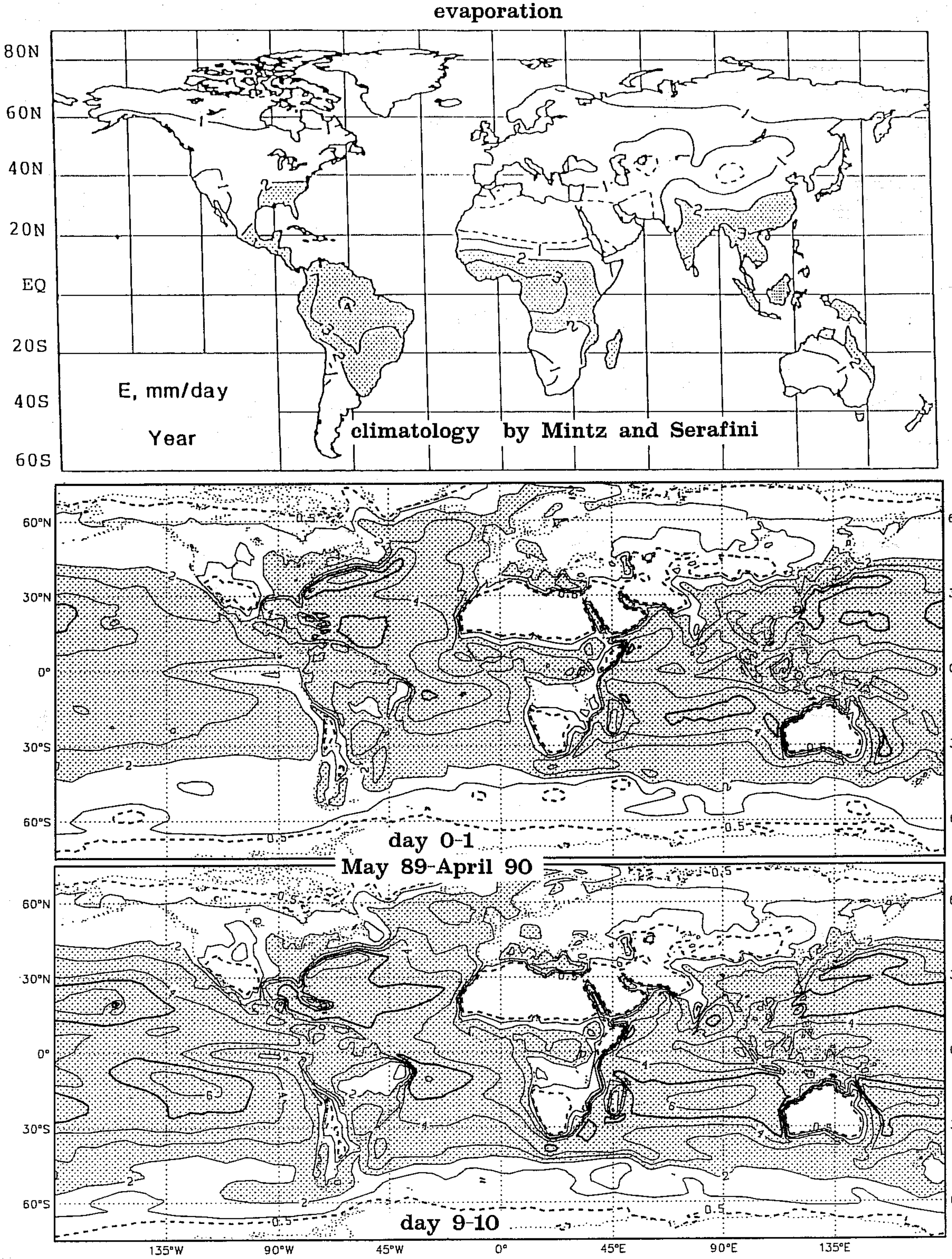


Fig. 7 Annual mean evaporation in the ECMWF model from May 89 to April 90 for the day 0-1 and day 9-10 forecasts and in the climatological estimates by Mintz and Serafini (1989).
Contour interval is 1 mm/day plus an extra dashed contour at 0.5 mm/day.
Shading for more than 2 mm/day.

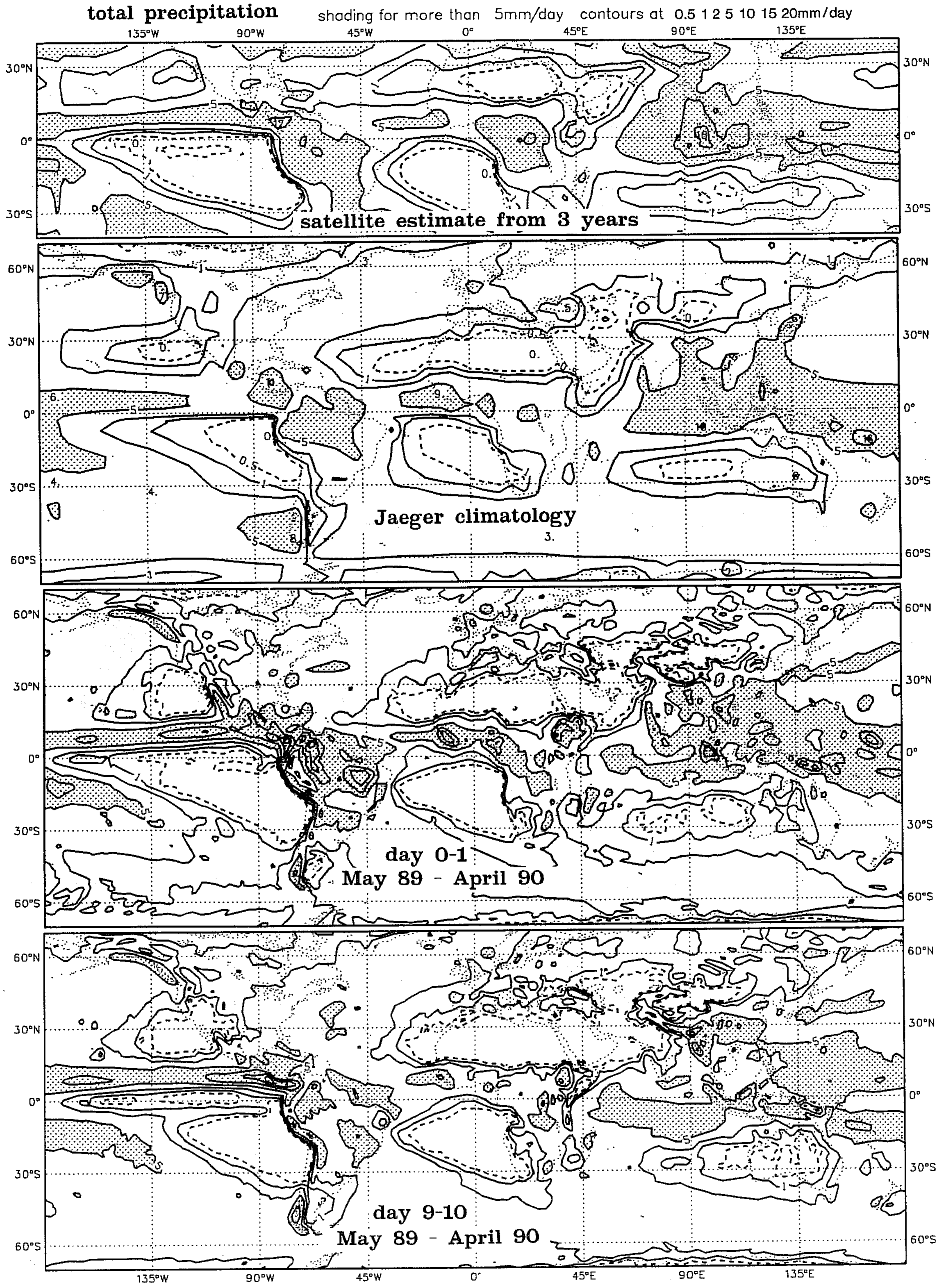


Fig. 8 Annual mean precipitation in the ECMWF model from May 89 to April 90 for the day 0-1 and day 9-10 forecasts, in the climatological estimates by Jaeger (1976) and in estimates from satellite measurements over 3 years (Arkin, Pers. Comm.). Contours at 0.5, 1, 2, 5, 10, 15 and 20 mm/day. The 0.5 mm/day contour is dashed. Shading for more than 5 mm/day.

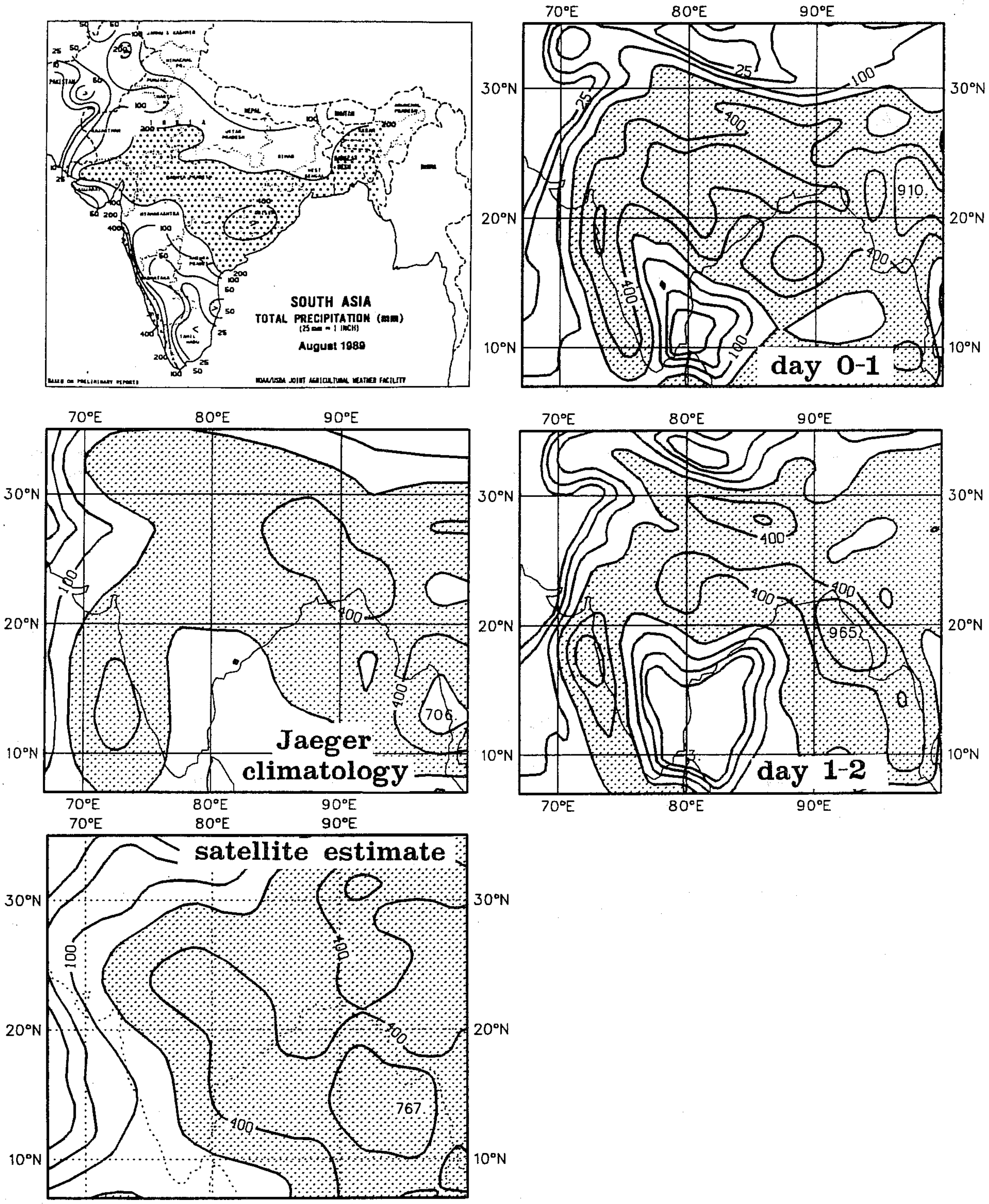


Fig. 9 Precipitation over India during August, 1989. Climatological estimates by Jaeger (1976) are compared with manual analysis by NOAA/USDA (1989), with estimates from satellite measurements (NOAA/CAC, 1989) and with ECMWF day 0-1 and day 1-2 forecasts. Contours at 25, 50, 100, 200, 400 and 600 mm. Shading for more than 200 mm.

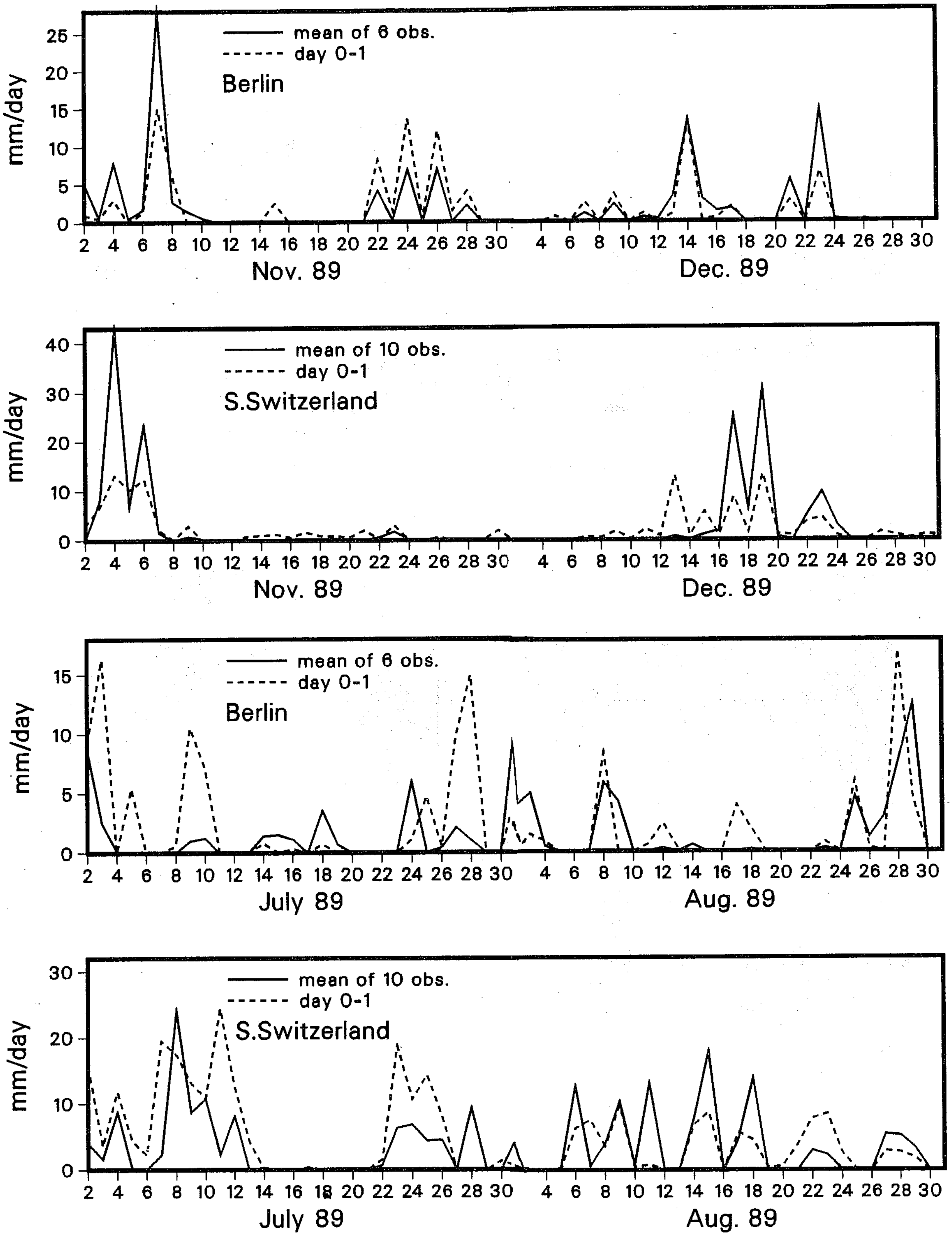


Fig. 10 Daily mean precipitation at selected model grid points (1.125° x 1.1213°) during July and August 1989 and November and December 1989. Values at day X is the accumulated precipitation between 12 GMT at day X-1 and 12 GMT at day X. Observations are averages of all available SYNOP stations for which the grid point representative. The number of stations involved for each gridpoint is given. Below the stations used for each grid point are listed:

Berlin	09379, 09385, 09490, 10381, 10382, 10384
S. Switzerland	06672, 06750, 06753, 06759, 06760, 06762, 06770, 06782, 06783, 06786

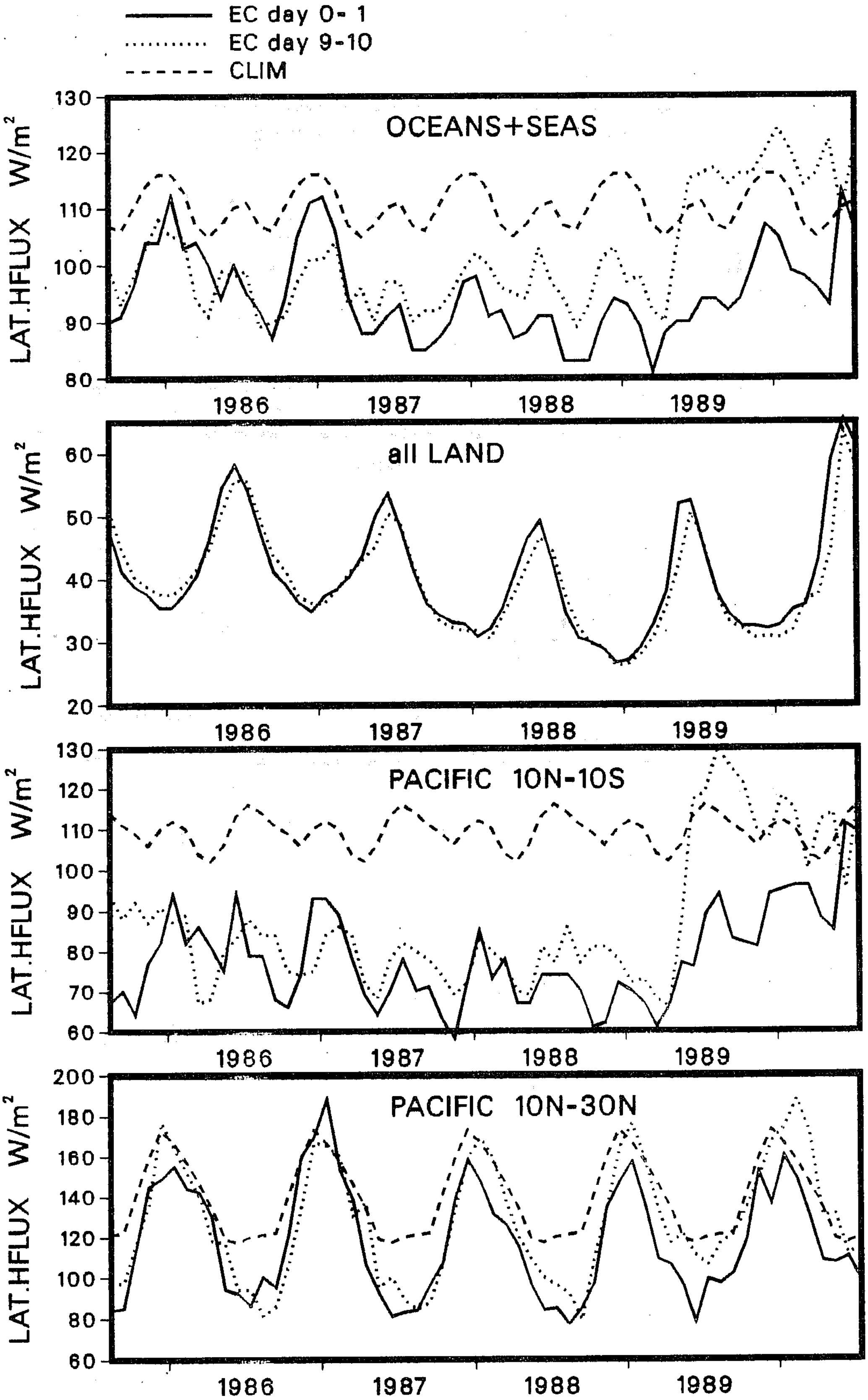


Fig. 11 Time series of latent heat fluxes for selected areas. For oceanic areas only grid points have been chosen for area averages for which climatological values are available.

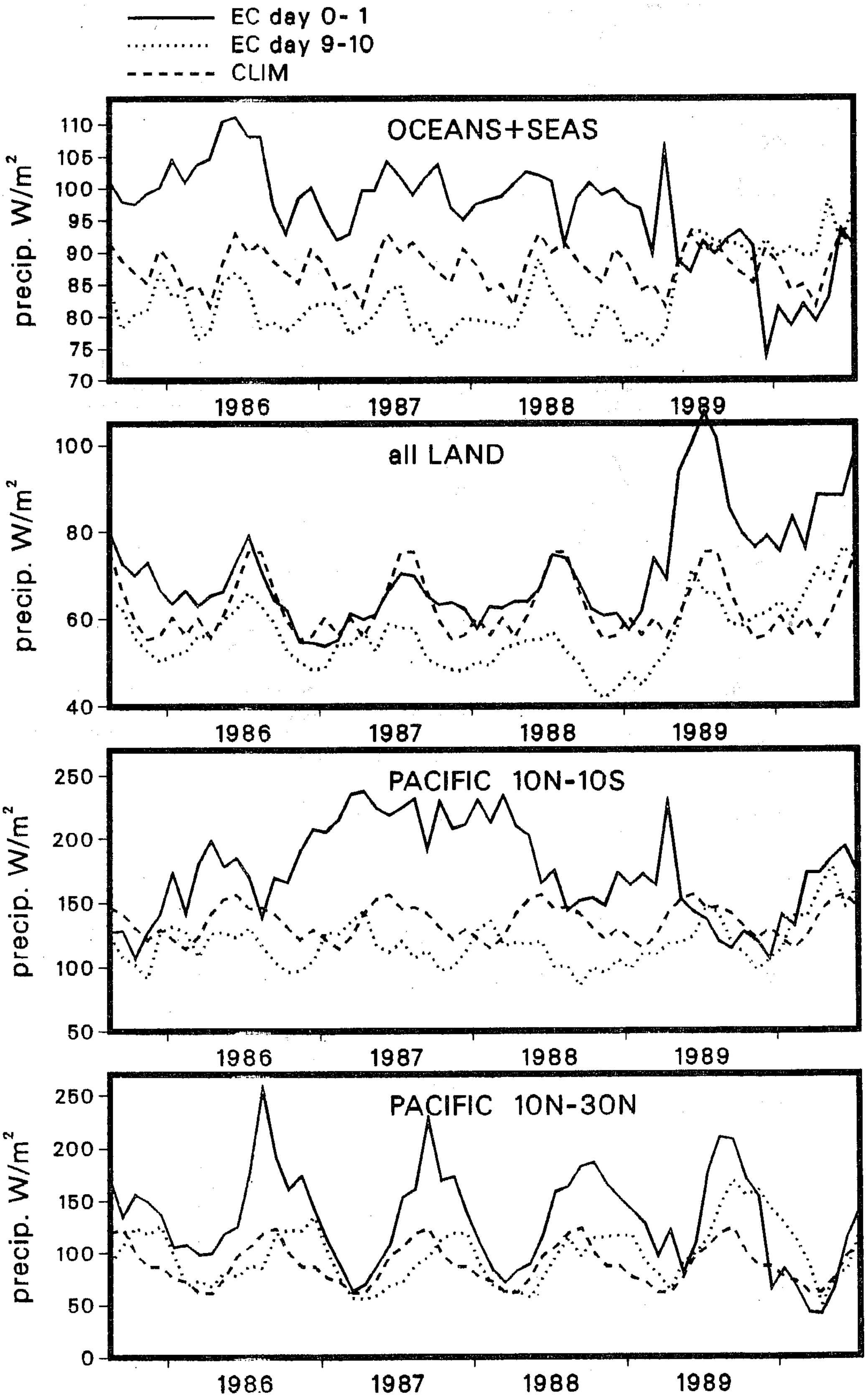


Fig. 12 Time series of monthly mean precipitation averaged over selected areas. Climatological estimates are compared with ECMWF day 0-1 and day 9-10 forecasts.

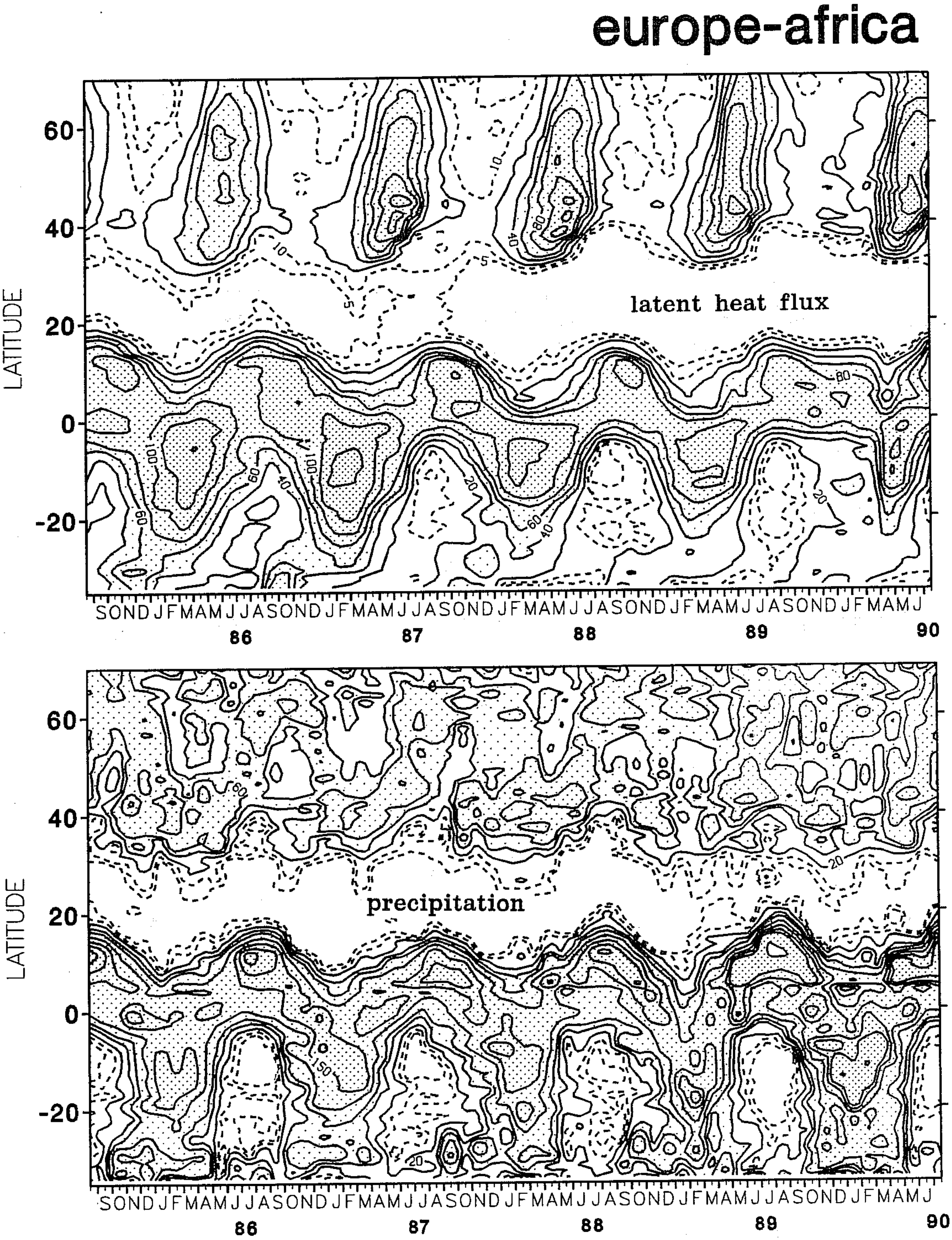


Fig. 13 Latitude-time cross-section of zonal mean latent heat fluxes and total precipitation in the monthly mean day 0-1 forecasts over continental grid points for the section Europe/Africa (20°W - 50°E).
Contour interval for latent heat flux: 20 W/m²; extra dashed contours at 5 and 10 W/m². Contours for precipitation at 5, 10, 20, 40, 60, 100, 150, 200, 250 and 300 W/m². Contours at 5 and 10 W/m² are dashed.

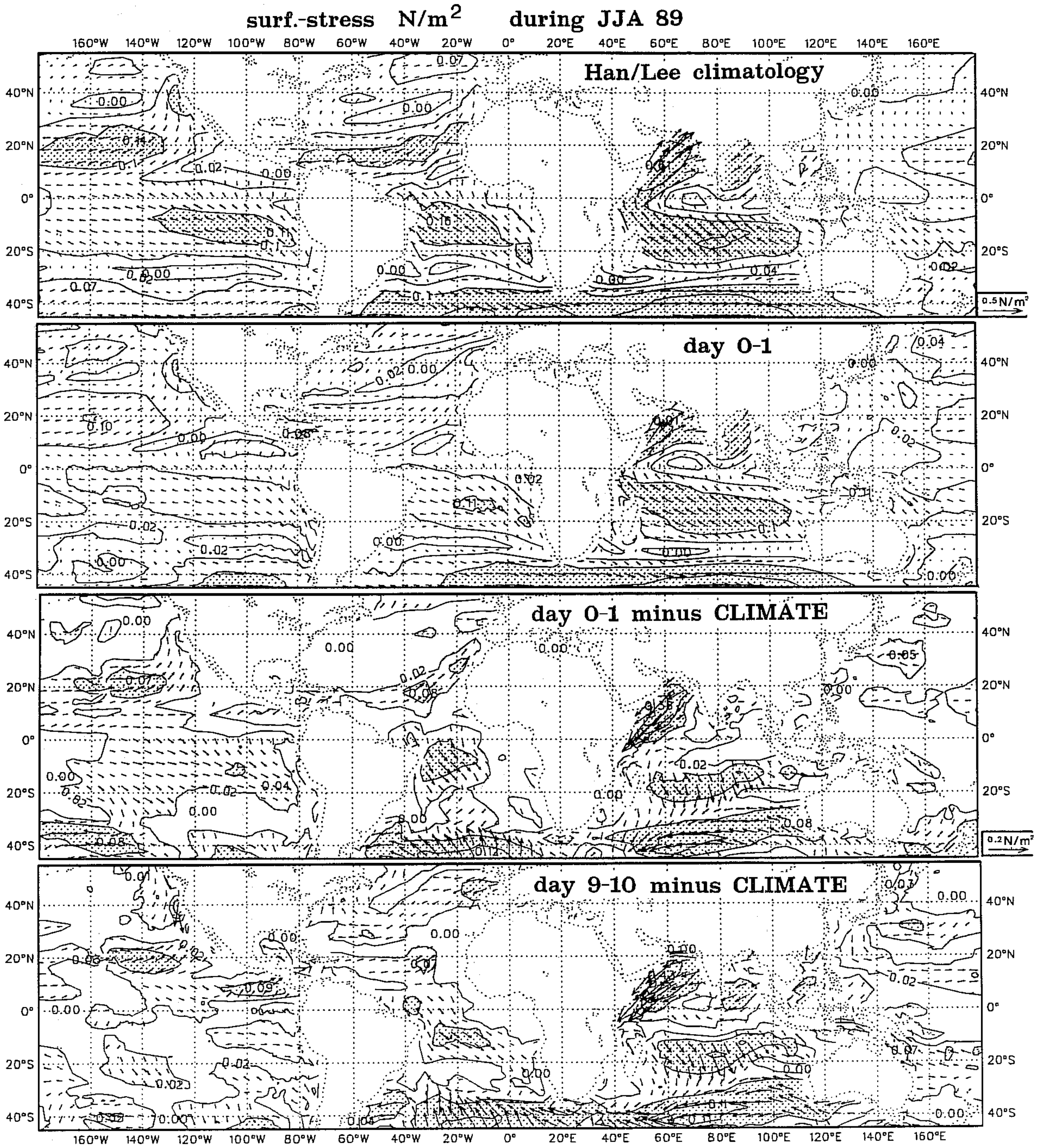


Fig. 14 Surface stresses for the season June to August.

a) Climatological estimate by Han and Lee (1981)

b) ECMWF day 0-1 forecasts during JJA 89

c) Difference between day 0-1 forecasts and the climatological estimate

d) Difference between day 9-10 forecasts and the climatological estimate.

Contours at 0.02, 0.05, 0.1, 0.2 and 0.5 N/m^2. Shading: a) and b) stresses larger than 0.1 N/m^2, c) and d) stress differences larger than 0.05 N/m^2.

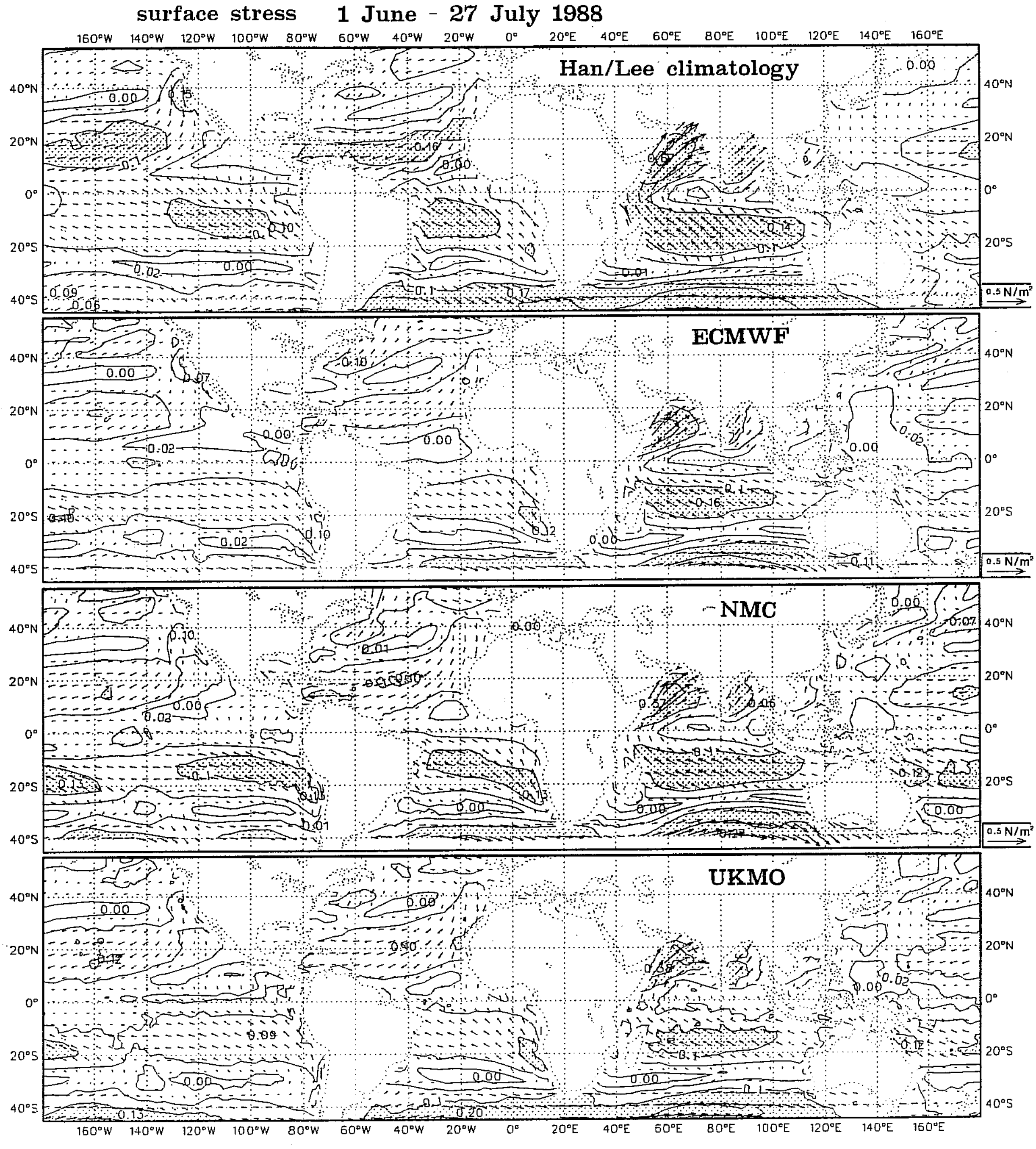


Fig. 15 Surface stresses in climatological estimates by Han and Lee (1981) for June and July and in short range forecasts by ECMWF, UKMO and NMC during 1 June to 27 July 1988.
Contours at 0.02, 0.05, 0.1, 0.2 and 0.5 N/m². Shading for stresses larger than 0.1 N/m².

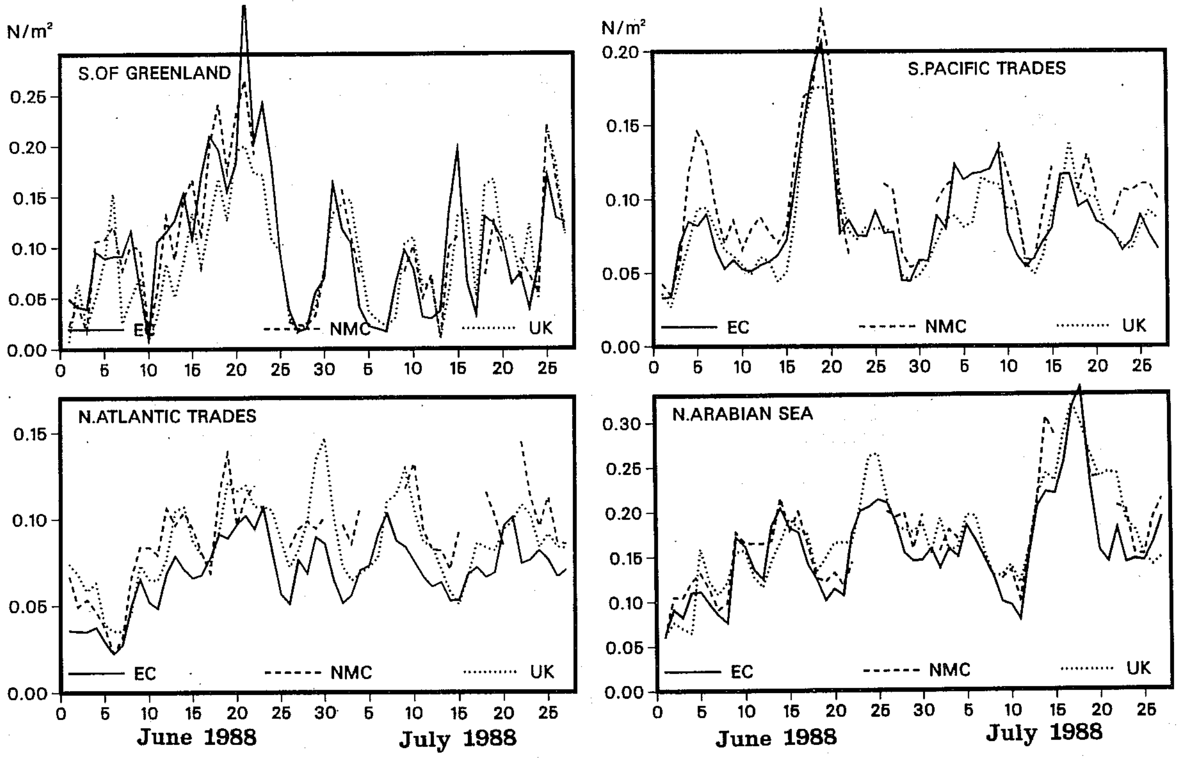


Fig. 16 Daily surface stresses averaged over selected areas in operational short range forecasts by ECMWF, UKMO and NMC for the period 1 June to 27 July 1988.

South of Greenland	53° - 60°N, 20° - 42°W
North Atlantic Trades	15° - 25°N, 33° - 50°W
South Pacific Trades	10° - 20°S, 95° - 130°W
North Arabian Sea	11° - 22°N, 62° - 71°E.

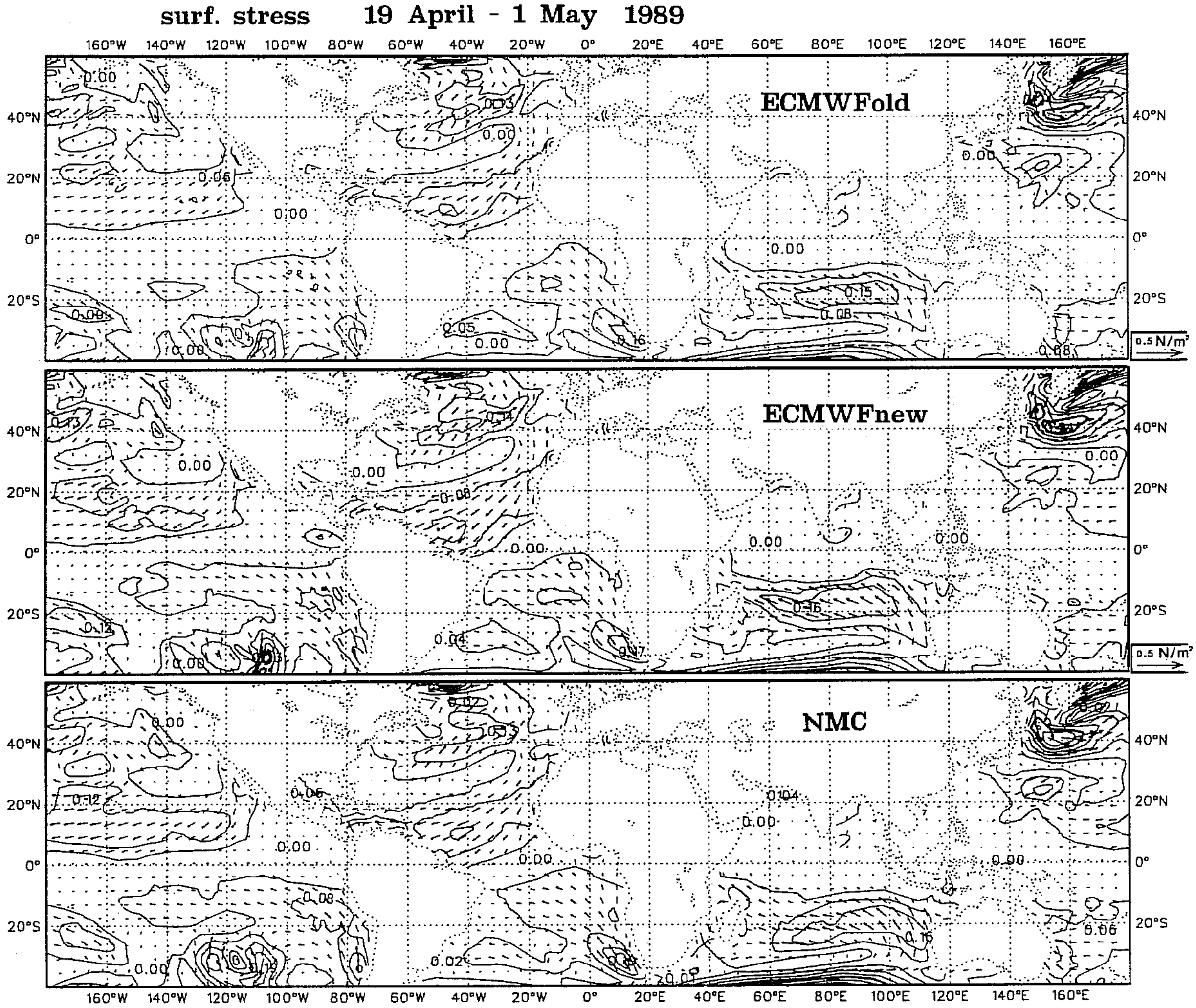


Fig. 17 Surface stresses in short range forecasts by two versions of the ECMWF model and by the NMC model during 19 April to 1 May 1989.
Contour interval 0.04 N/m².

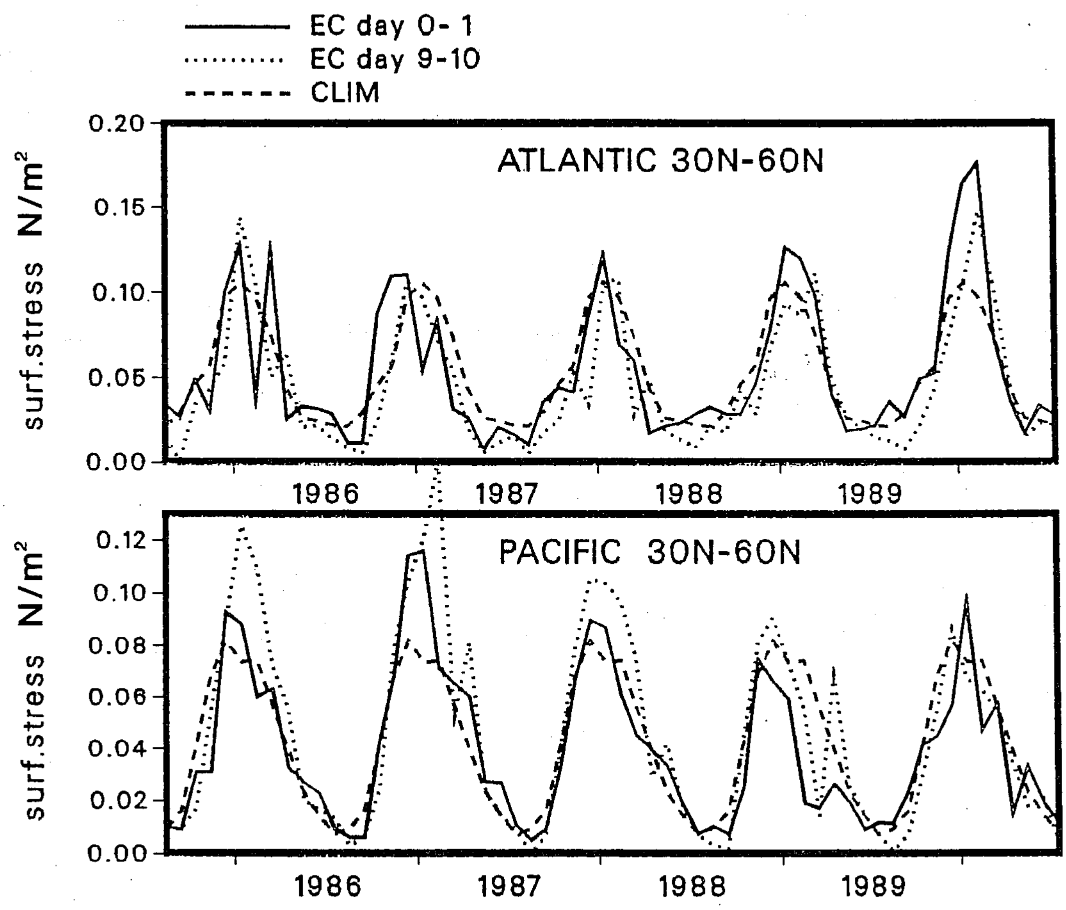


Fig. 18 Time series of monthly mean surface stress averaged over the Pacific and Atlantic ocean between 30° and 60°N. For area averaging only grid points have been chosen for which climatological estimates are available.

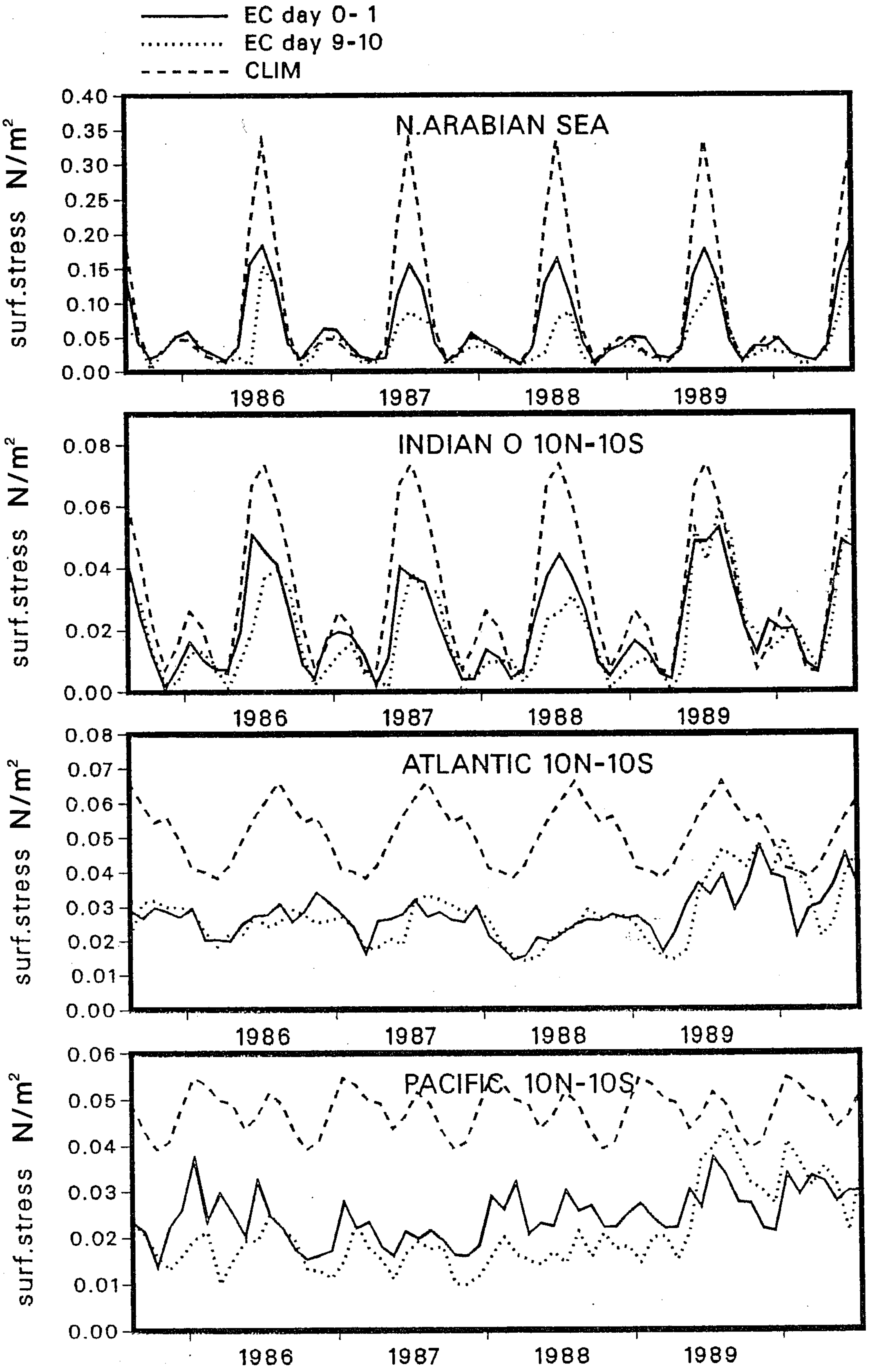


Fig. 19 Same as Fig. 18 but for the Pacific, the Atlantic and the Indian Ocean between 10°N and 10°S as well as for the North Arabian Sea (61°-71°E, 11°-22°N).