THE HYDROLOGICAL CYCLE IN THE ECMWF SHORT RANGE FORECASTS

K. Arpe
European Centre for Medium-Range Weather Forecasts
Shinfield Park, Reading, U.K.

Abstract

Precipitation and latent heat flux forecasts by the ECMWF model have been compared with other estimates of these quantities. In the northern hemisphere extra-tropics the latent heat flux over oceans and the precipitation over continents in the short range forecasts are probably good estimates of the truth. The day to day as well as the interannual variability in these latitudes seem to be realistic. In the southern hemisphere extra-tropics there is a strong spin-up in the precipitation forecasts probably with too low precipitation amounts in the short range forecasts. It is speculated that inconsistent use of satellite data leads to a weakening of large scale rising motions between 40°S and 60°S. Also the latent heat flux in these latitudes are probably too low due to a too moist 1000 mb humidity analysis. Over subtropical deserts the precipitation amounts in the forecasts agree with climatological estimates. Contrary to climatological estimates this precipitation is not evaporated but runs-off. In the tropics, especially over mountainous areas, the short range forecasts (average for the first 24 hours) with the present model tend to overpredict precipitation amounts but still with reasonable distributions. Averages between day 1 and 2 give probably a good estimate of the truth except over the eastern Pacific where there is an overestimation, also in the medium range forecasts. Strong underestimation of latent heat fluxes over tropical oceans in the short range forecasts have been considerably reduced with a recent model change. There are still areas e.g. the southern hemisphere sub-tropical Pacific with too low evaporation due to too moist 1000 mb analyses probably in connection with an inconsistent use of satellite observations. The interannual variability of monthly mean evaporation and precipitation in the short range forecasts reflects partly atmospheric anomalies but especially in the tropics, also reflects larger amplitude variations due to changes in the analysis/forecasting scheme.

1. INTRODUCTION

The atmospheric circulation is mainly forced by heating due to condensation of water vapour in the tropics and by cooling through radiation processes in polar regions. It is essential to simulate this energy and water cycle of the atmosphere satisfactorily in climate models but these processes are also of importance for medium range forecast models. Validation of the diabatic processes in the model is hampered by a lack of knowledge of the true values and by strong interactions between different processes within the model.

Because of such interactions the study will concentrate on short range forecasts. For this forecast range inconsistencies between the analysis and model formulations may play an important rôle. Inconsistencies can result from systematically wrong observational data, from an incorrect usage of observational data, and from systematic errors of the model. If observational data do not fit to the first guess field because of a systematic error in the model providing the first guess, the analysis/forecasting scheme may reject the observation, leading to a wrong analysis, or may accept it. In the latter case the model will eventually make an adjustment back to its preferred structure, a process known as spin-up.

To study the reasonableness of the model-produced diabatic forcings, global budgets of the energy and water cycle are compared with climatological estimates in Section 3. The study will concentrate on the atmospheric water budget. Comparison of the model based estimates with a variety of other estimates of evaporation and precipitation for different areas of the earth are carried out in Sections 4 and 5. The importance of model formulation can be seen from comparisons between different models (Section 4) or by investigating the variability of the model output through the years with a changing model (Section 6). In the latter investigation variations due to atmospheric anomalies and due to model changes have to be separated. It will be shown that all estimates used in this comparison bear considerable uncertainties but nevertheless some clear conclusions will be drawn in Section 7.

This study is not only carried out with the view of model validation but will also try to answer the question if short range forecast values of precipitation and evaporation can be used as estimates of the truth, e.g. for diagnostic studies or for forcing oceanic models.

2. DATA

The ECMWF data assimilation scheme is an intermittent four-dimensional optimum interpolation scheme (Bengtsson et al., 1982) in which a global multivariate analysis is carried out at 6 hour intervals (Shaw et al., 1987). The six-hour forecast from the previous (initialized) analysis is used as a first guess for the new analysis. An initialization is needed to prevent spurious noise in the six-hour forecasts which would otherwise cause problems with quality control of observations in subsequent analysis (Wergen, 1989). The forecast is carried out with the operational ECMWF medium range model which was (for the period of investigation) a spectral T106 model with 16 or 19 hybrid levels in the vertical (Simmons et al., 1989). Important subgrid scale processes have been accounted for by the parametrization schemes (Tiedtke et al., 1988, Tiedtke, 1989, Morcrette, 1990, Miller and Palmer, 1987). During the period of investigation the analysis/forecasting scheme has undergone modifications which are listed in Annex 1 together with references to publications in which the modifications are discussed in detail. The sea surface temperature is the one analysed by NMC and is kept constant during the forecasts.

Latent heat fluxes in the short range forecasts have been compared with those by the UK Meteorological Office (UKMO) and the National Meteorological Center, Washington (NMC). The UKMO analysis/forecasting scheme differs considerably from the ECMWF one: the analysis is carried out by a repeated insertion of observations into a forecasting model over a period; the adiabatic part of the model is formulated in finite differences; and no initialization is applied. All models differ in their quality control procedures and in their parametrization schemes of subgrid scale processes. These comparisons are further discussed by Arpe et al.(1988).

Climatological data sets used in this study are those by Jaeger (1976) for precipitation, Mintz and Serafini (1989) for evaporation over land, and Oberhuber (1988) for evaporation over oceans. 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.

All these differences in the analysis/forecasting schemes and estimates of climatology 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.

The fact that all models or climatological estimates give similar results is no guarantee that estimates of precipitation or latent heat flux are correct. 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.

Despite all these uncertainties and possibilities of differences between data sets of surface fluxes it will however be shown below that 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.

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 for references). 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 residuum suggests low reliability in at least one of the components and this is taken up in the discussion below.

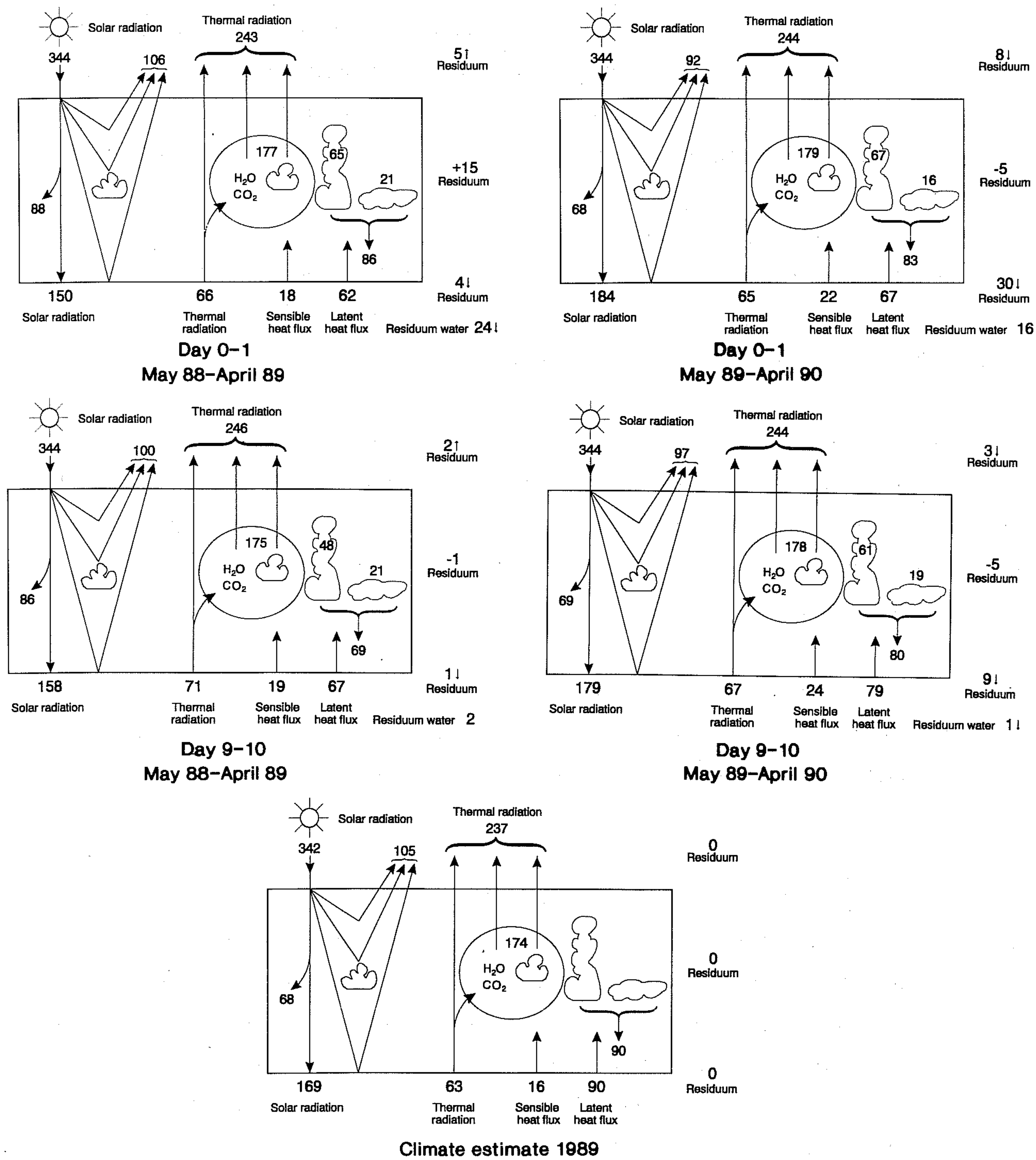

Fig. 1 Global annual mean energy and water cycle derived from day 0-1 (upper panels) and day 9-10 forecasts (middle panels) and climatological estimates of these cycles by Ramanathan et al. (1989) (lowest panel). Model data from two years with different parametrization schemes are compared. Units: W/m².

The latent heat fluxes in the day 0-1 forecasts are lower than they are for day 9-10 forecasts, they are also lower than the climatological estimates and by implication are low when compared with climatological as well as short range model 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 as discussed in the next section.

The day 9-10 forecast values of evaporation in the range 67-79 W/m^2 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 global mean evaporation of 75 to 84 W/m^2 and Jaeger (1976) gives precipitation amounts from which evaporation values of 82 W/m^2 can be inferred. For the year 1988/89 the day 9-10 values are probably 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 with increased albedo, less insolation at the ground (about 10 W/m^2) and less sensible heat and radiative fluxes from the ground (around 5 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 are 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) (90 W/m^2) but agree with those by Jaeger (1976) (82 W/m^2) and Hoyt (1975) (75-84 W/m^2).

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 (Janowiak and Arkin, 1990) 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 (1976) - 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.

For annual and global means the evaporation and precipitation should balance. In the day 0-1 forecasts large imbalances result from too low evaporation and this problem will be further studied in the later 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 (Beljaars and Miller, 1990).

4. GEOGRAPHICAL DISTRIBUTION 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, since 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 (ECMWF has recently increased the value it uses 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

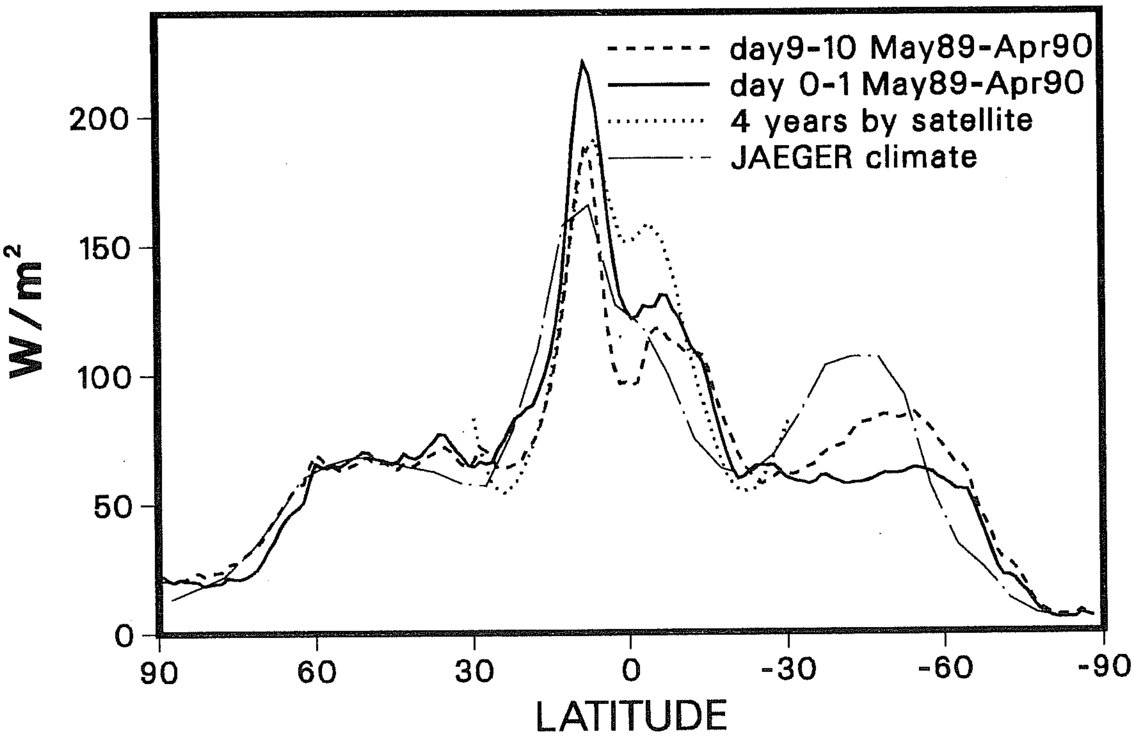

Fig. 2 Zonal and annual means of precipitation. Climatological estimates by Jaeger (1976) are compared with estimates from satellite measurements over 4 years (Janowiak and Arkin, 1990) and with ECMWF day 0-1 and day 9-10 forecasts during May 89 to April 90.

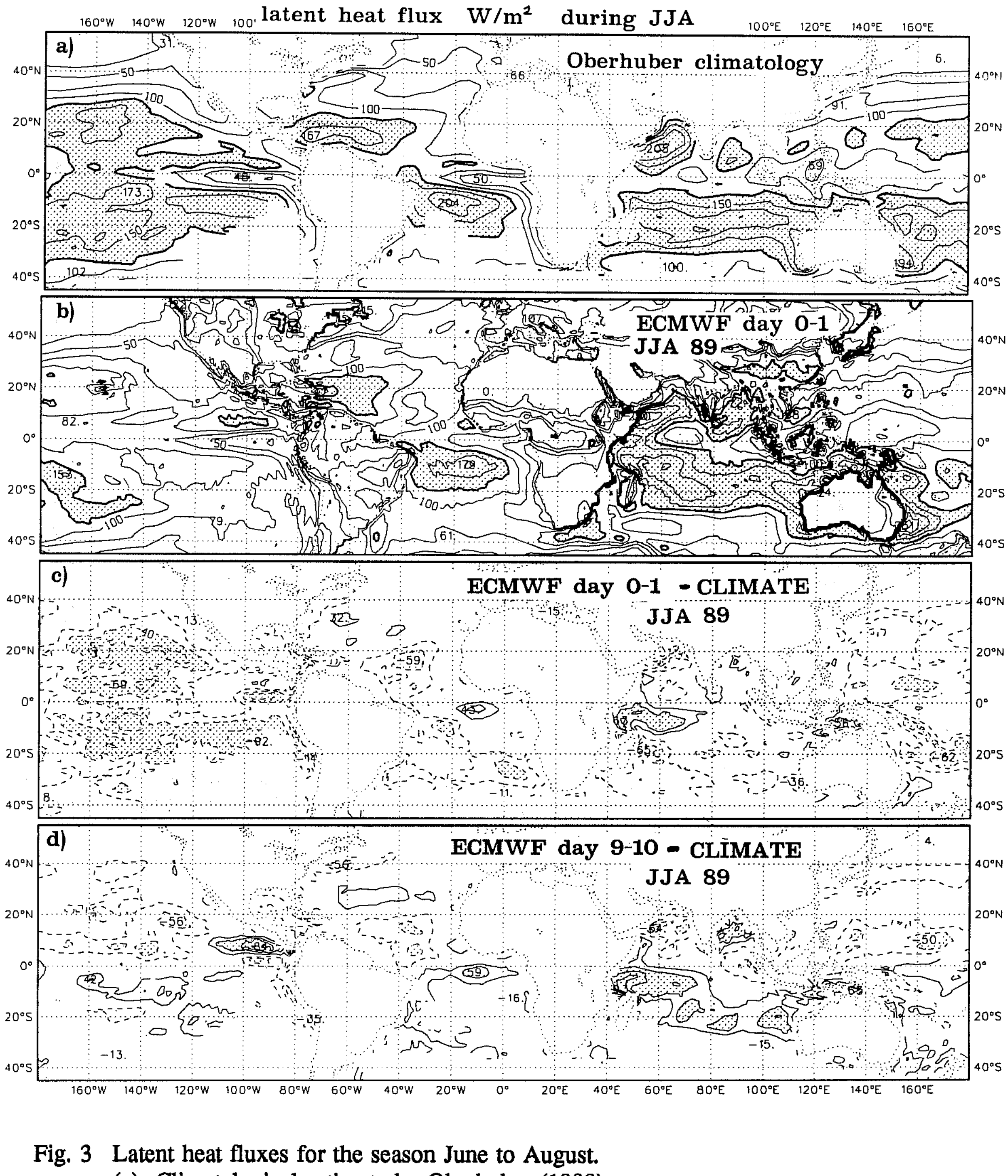

Fig. 3 Latent heat fluxes for the season June to August.
(a) Climatological estimate by Oberhuber (1988)
(b) ECMWF day 0-1 forecasts during 1989
(c) Difference between day 0-1 forecasts and the climatological estimate
(d) Difference between day 9-10 forecasts and the climatological estimate.
Contour 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.

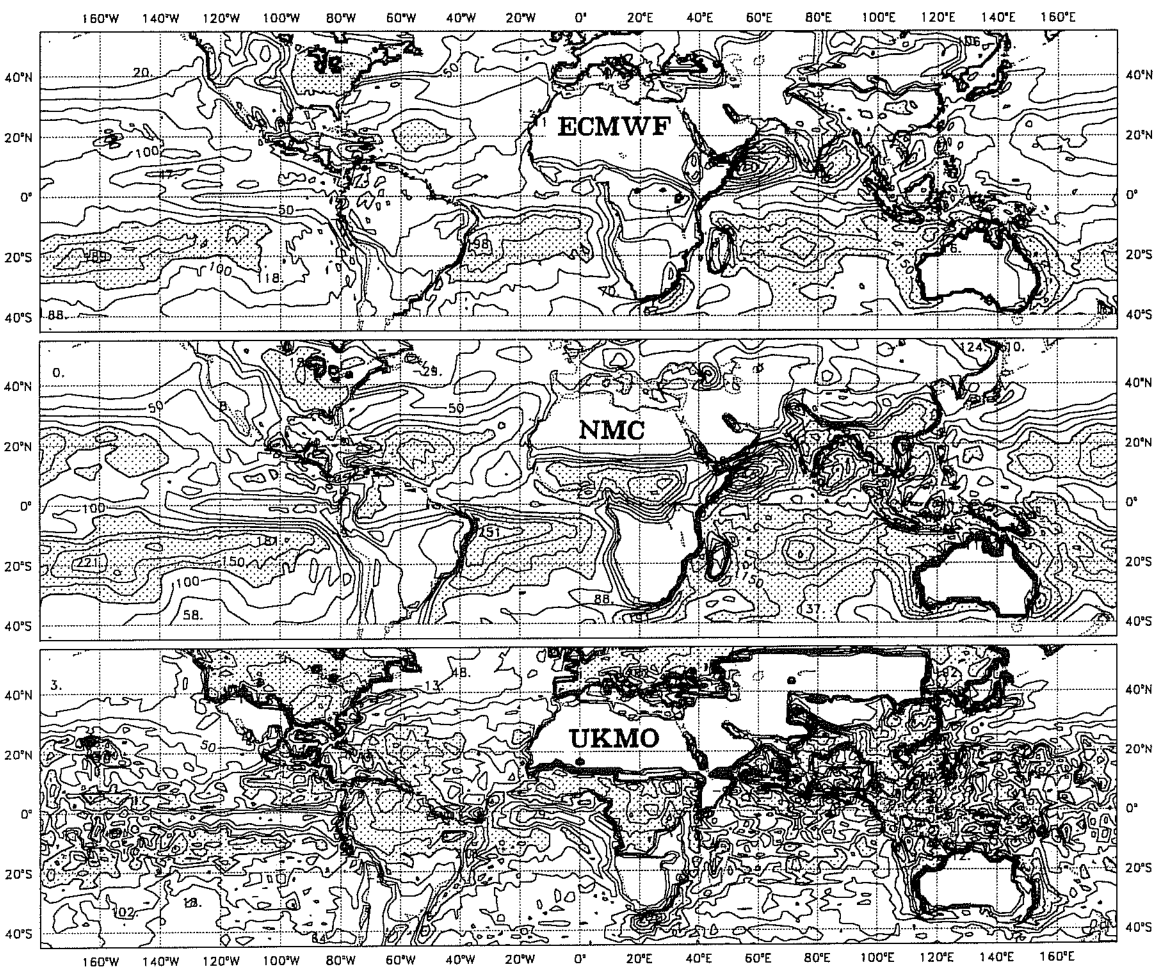

Fig. 4 Latent heat fluxes in the short range forecasts by ECMWF, NMC and UKMO averaged over the period 1 June to 27 July 1988. Contour interval: 25 W/m^2. Shading for more than 125 W/m^2.

latent heat fluxes in short range forecasts from different models (ECMWF, NMC, UKMO) operational during 1988 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 (see below). In Fig. 4 ECMWF latent heat fluxes are also low compared to NMC over the Trade wind areas partly because of lower surface stresses in the ECMWF model (Arpe et al., 1988). Latent heat fluxes in the ECMWF model are low as well in areas of tropical precipitation and in this respect the ECMWF model could be more realistic because it accounts for evaporation from falling convective 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 is 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 explore 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 areas and these report often only during day time. Comparisons with observational data and analysis experiments with and without the use of satellite observations suggest that the too moist low-level analysis is caused by satellite observations. The source of these biases is not yet clear, since the humidity analysis is affected both by humidity observations and by the temperature. Further work is therefore needed in order to develop procedures to use satellite data more effectively over oceanic areas.

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. 6) 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

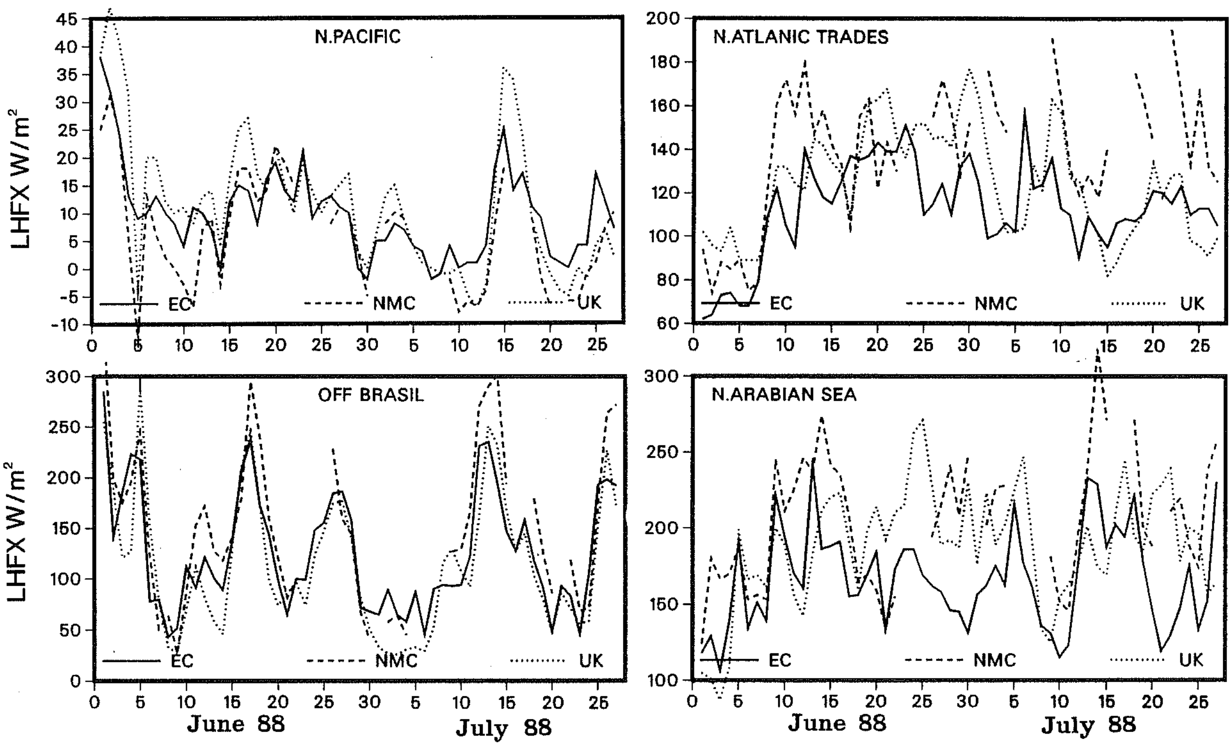

Fig. 5 Daily latent heat fluxes for selected areas in operational short range forecasts by ECMWF, UKMO and NMC for the period 1 June to 27 July 1988.

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

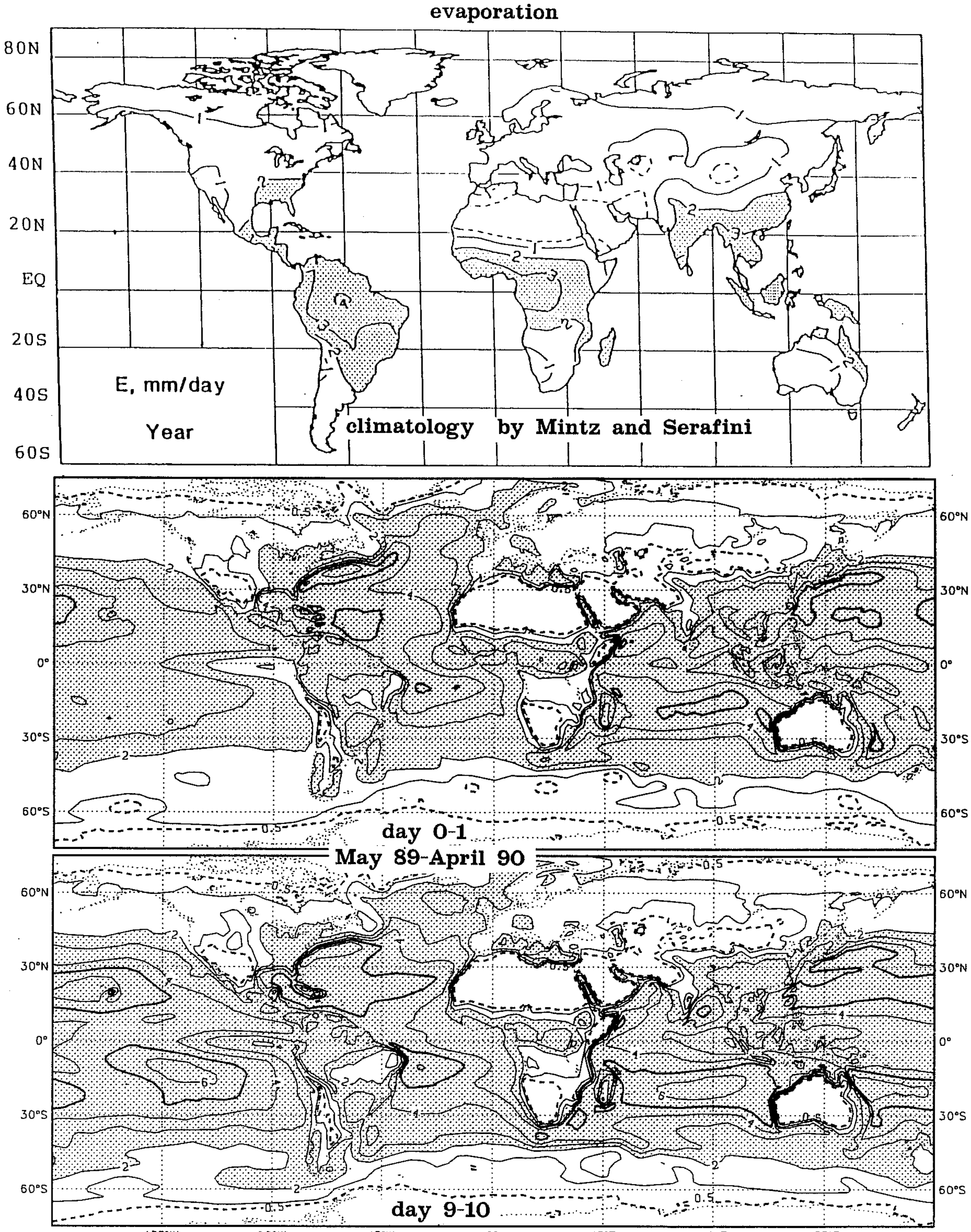

Fig. 6 Annual mean evaporation in the ECMWF model from May 89 to April 90 for the day 0-1 and day 9-10 forecasts and in the climatological estimates by Mintz and Serafini (1989). Contour interval is 1 mm/day plus an extra dashed contour at 0.5 mm/day. Shading for more than 2 mm/day.

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 larger than 1.0 mm/day over considerable areas. 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. 7) probably assuming the run-off to be small while there must be considerable run-off in the ECMWF model 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. The criteria for run-off should be further modified for desert areas to reduce the run-off even more.

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. 7). 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. 7 annual mean precipitation in the model (May 89-April 90) as well as climatological estimates by Jaeger (1975) and estimates from satellite observations by Janowiak and Arkin (1990) 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.

In the comparison of zonal mean precipitation by different estimates (Fig. 2) it was already shown that the model values agreed very well with the climatological estimates in northern hemisphere mid-latitudes. Also the geographical distribution in Fig. 7 exhibit a good similarity in these latitudes. The quality of the short range forecasts has been further investigated for a few grid points over Europe. Only grid points have been chosen for which several observing stations were available. Fig. 8 shows time series of daily mean 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 a

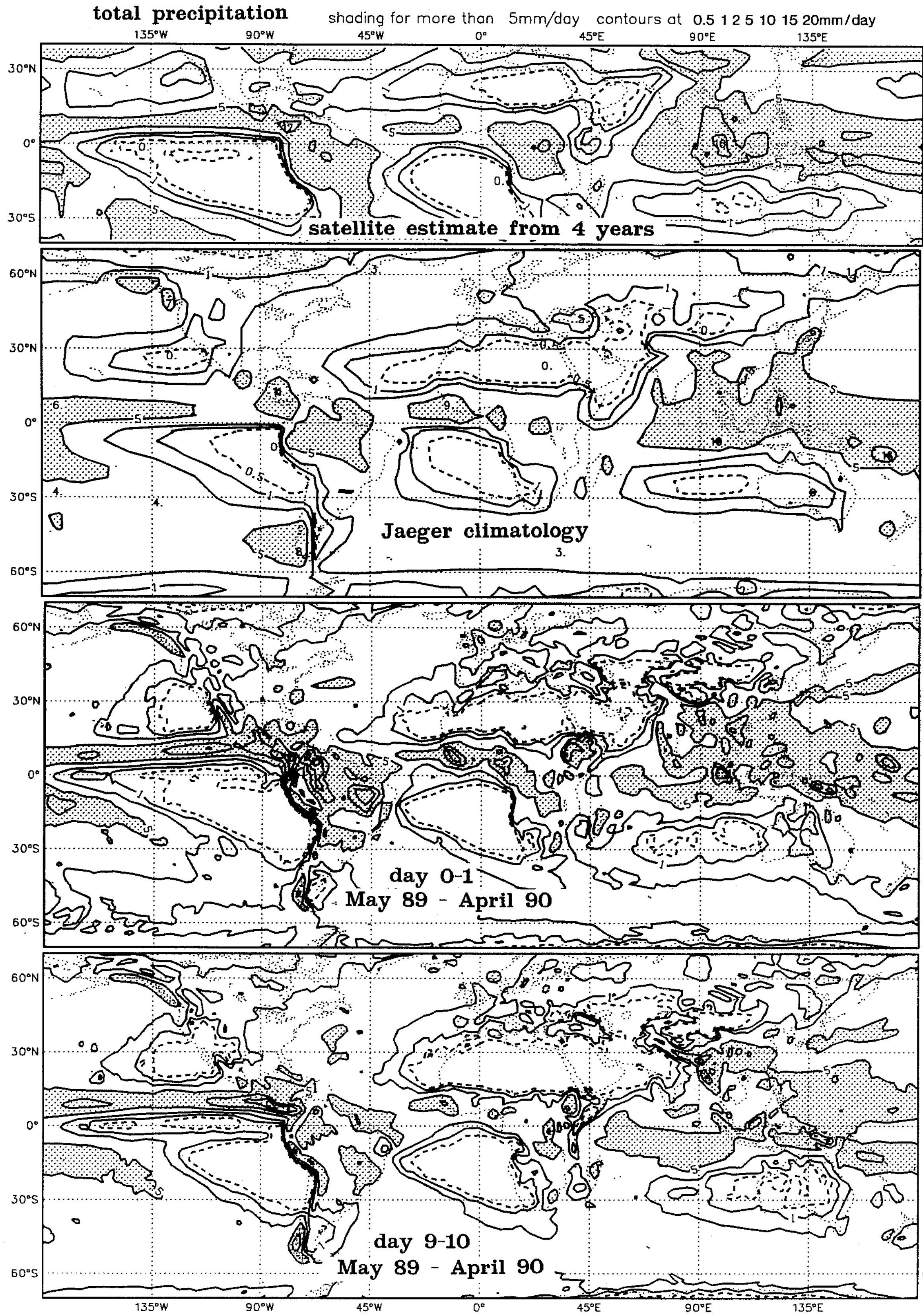

Fig. 7 Annual mean precipitation in the ECMWF model from May 89 to April 90 for the day 0-1 and day 9-10 forecasts, in the climatological estimates by Jaeger (1976) and in estimates from satellite measurements over 4 years (Janowiak and Arkin, 1990). Comm.). Contours at 0.5, 1, 2, 5, 10, 15 and 20 mm/day. The 0.5 mm/day contour is dashed. Shading for more than 5 mm/day.

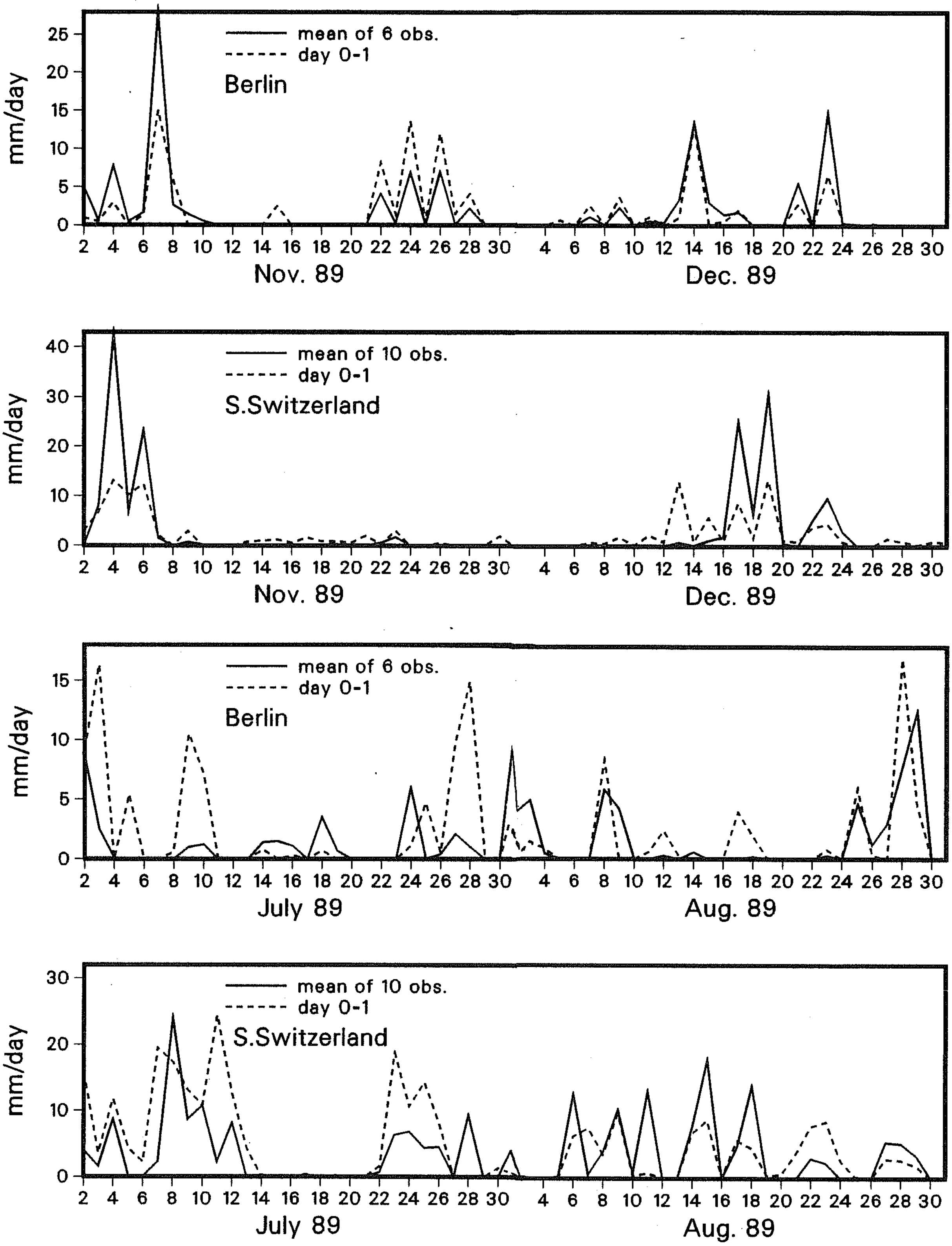

Fig. 8 Daily mean precipitation at selected model grid points (1.125° x 1.1213°) during July and August 1989 and November and December 1989. Values at day X is the accumulated precipitation between 12 GMT at day X-1 and 12 GMT at day X. Observations are averages of all available SYNOP stations for which the grid point is representative. 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

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. Day 1-2 forecasts have also been compared with observations and it is obvious that day 0-1 precipitation forecasts are superior to the day 1-2 values.

In the southern hemisphere extra-tropics the zonal means (Fig. 2) of the climatological estimate differed considerably from the short range forecast values. The differences are largest (about 1.5 mm/day) between 40°S and 60°S. These differences do not show up so clearly in Fig. 7 because of the chosen contour levels and the flat distribution. Only over the eastern Pacific in these latitudes the differences are more obvious but the differences are evenly distributed around the whole latitude belt. Only very few observational data are available except those by satellite. From the large differences between day 0-1 and day 9-10 precipitation values one can deduce that these observational data must have a strong impact on the analysis which leads to a reduction of precipitation, mainly of large scale (frontal) precipitation. Connected with this lower precipitation in the short range forecasts is a weaker rising motion or enhanced subsidence in the analysis compared to the day 10 forecasts in this latitudinal belt. Klinker (pers. comm.) has found for the northern hemisphere storm tracks that the inclusion of temperature soundings from satellite in the analysis reduces the diabatic heating in the short range forecasts. It is not obvious how satellite observations can cause such a change in the Ferrel circulation, possible causes are the reduction of structures in the vicinity of cyclones or increases of static stability which would delay cyclone developments.

Over tropical continents the short range forecasts agree with the satellite estimates, both estimating larger amounts than Jaeger's climatology and the medium range forecasts. In this respect Jaeger's climatology should be more reliable. Also comparisons with precipitation analysis by NOAA/USDA (1989) suggest that satellite estimates and short-range forecasts overestimate the precipitation over tropical continents.

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 (Beljaars and Miller, 1990) 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 as they agree with the climatological estimate. 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 while satellite estimates would still provide the largest values.

A good example which demonstrates the spin-up problem of precipitation of the tropics 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. A tongue with large amounts of precipitation from the Bay of Bengal into central India is present in all estimates and the estimate by satellite provides a position of this tongue which is nearest to the one in the manual analysis. 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 though the early onset of a systematic error of the atmospheric circulation in the model in this area may lead to a deterioration of the precipitation distribution. Also the precipitation amounts from satellite estimates seem to be too large.

Forecast experiments with different resolutions have shown that a high resolution will provide finer structures and larger extreme values but the impact on the amount of precipitation on a larger scale seems to be small except for very low resolutions like T21.

6. INTERANNUAL VARIABILITY OF THE HYDROLOGICAL CYCLE IN ECMWF FORECASTS

For selected areas the latent heat fluxes as well as the precipitation amounts 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.10. 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 and seas. 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 (Arpe and Burridge, 1990). 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

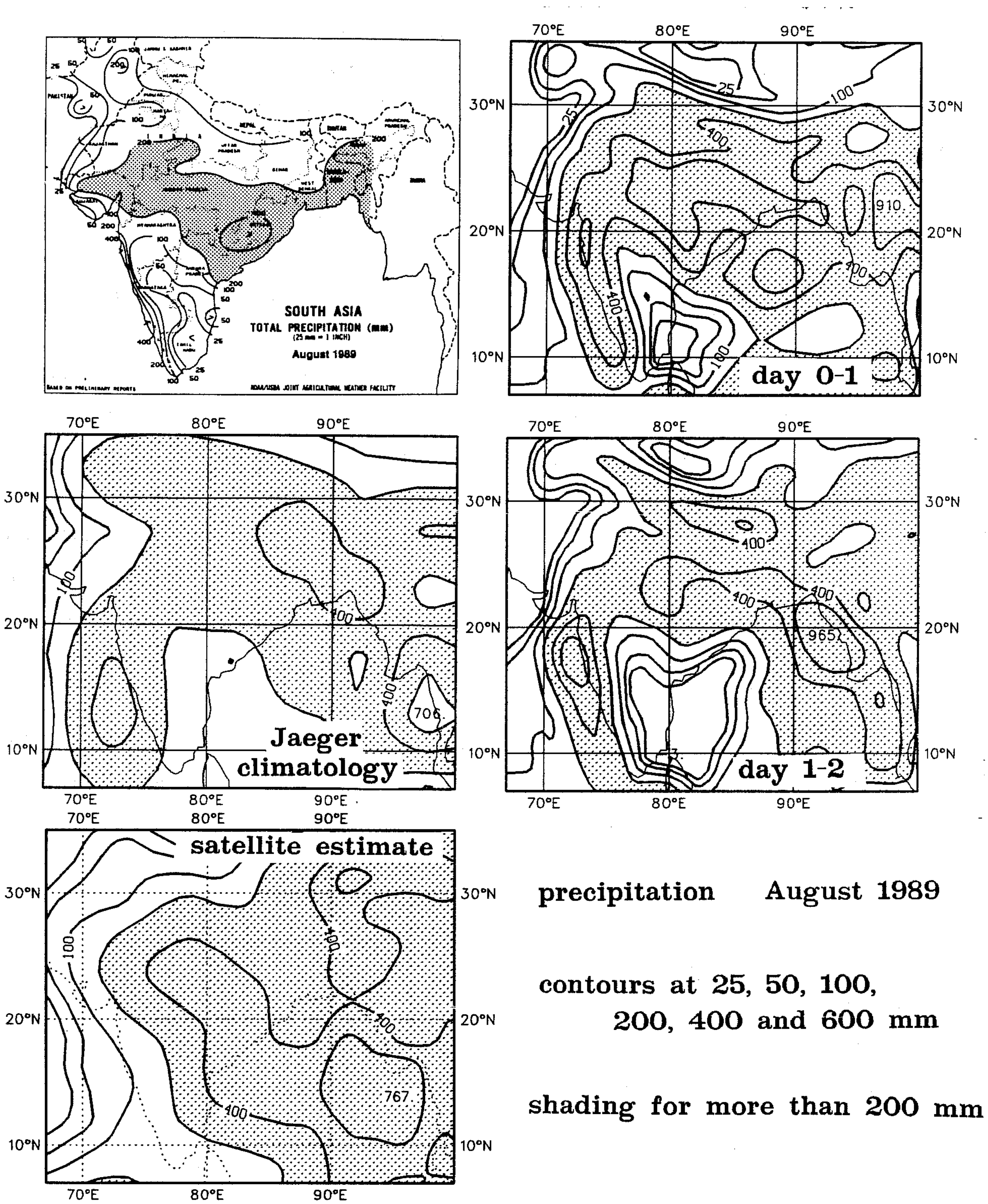

Fig. 9 Precipitation over India during August, 1989. Climatological estimates by Jaeger (1976) are compared with manual analysis by NOAA/USDA (1989), with estimates from satellite measurements (NOAA/CAC, 1989) and with ECMWF day 0-1 and day 1-2 forecasts. Contours at 25, 50, 100, 200, 400 and 600 mm.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

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). Some of the effects from model changes suggested here agree with findings from experiments carried out before the introduction of the model changes (see Annex 1 for references) but because of many interactions in the analysis/forecasting scheme one would need more extensive experiments to get statistically significant results.

For the average over all land grid points no climatological estimate was readily available and therefore only the two forecast 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 (run-off) are clearly indicated. The steep increases of precipitation over land with the May 89 model change 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 vaguely 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. 10 (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 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

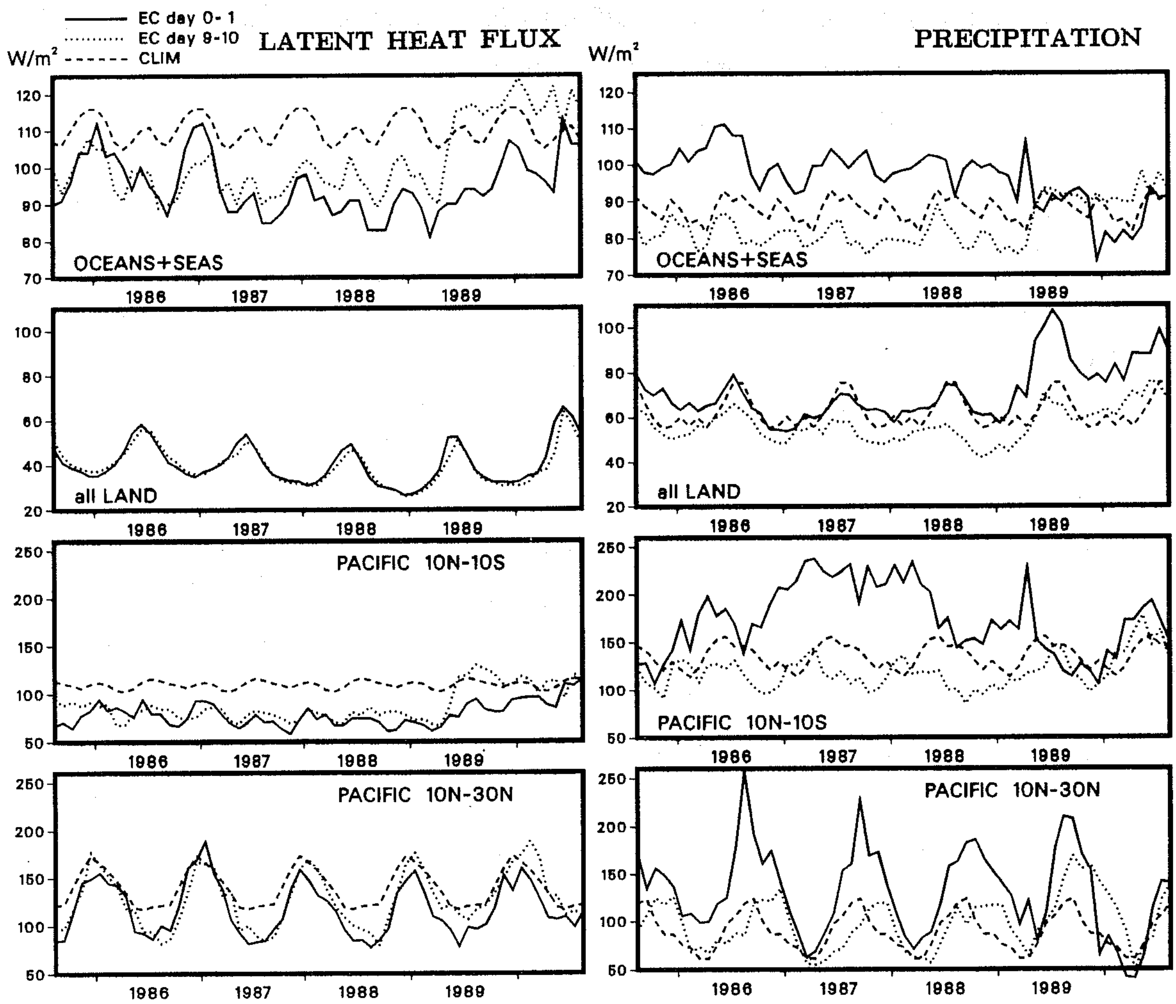

Fig. 10 Time series of monthly mean latent heat fluxes and precipitation for selected areas. For latent heat fluxes over oceanic areas only grid points have been chosen for area averages for which climatological values are available.

by Palmer et al. (1990) with the June 90 model version (increased evaporation at low wind speed) 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. 10 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 for 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. 10.

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. 10 it can be seen that at this time the change of the spin-up characteristics was even stronger when separating between continents and oceans. Over oceans the spin-up disappeared (though only for global means) 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. 11 as a latitude-time cross-section. For Europe the maximum evaporation during late spring has been increased strongly from 86 to 87, slightly around May 89 and again around May 90. The latter increases go hand in hand with an increase of precipitation in the day 0-1 forecasts. Increases around May 89 and May 90 are probably due to model changes at that time but the strong increase from 1986 to 1987 cannot be assigned to the April 87 model change as this was

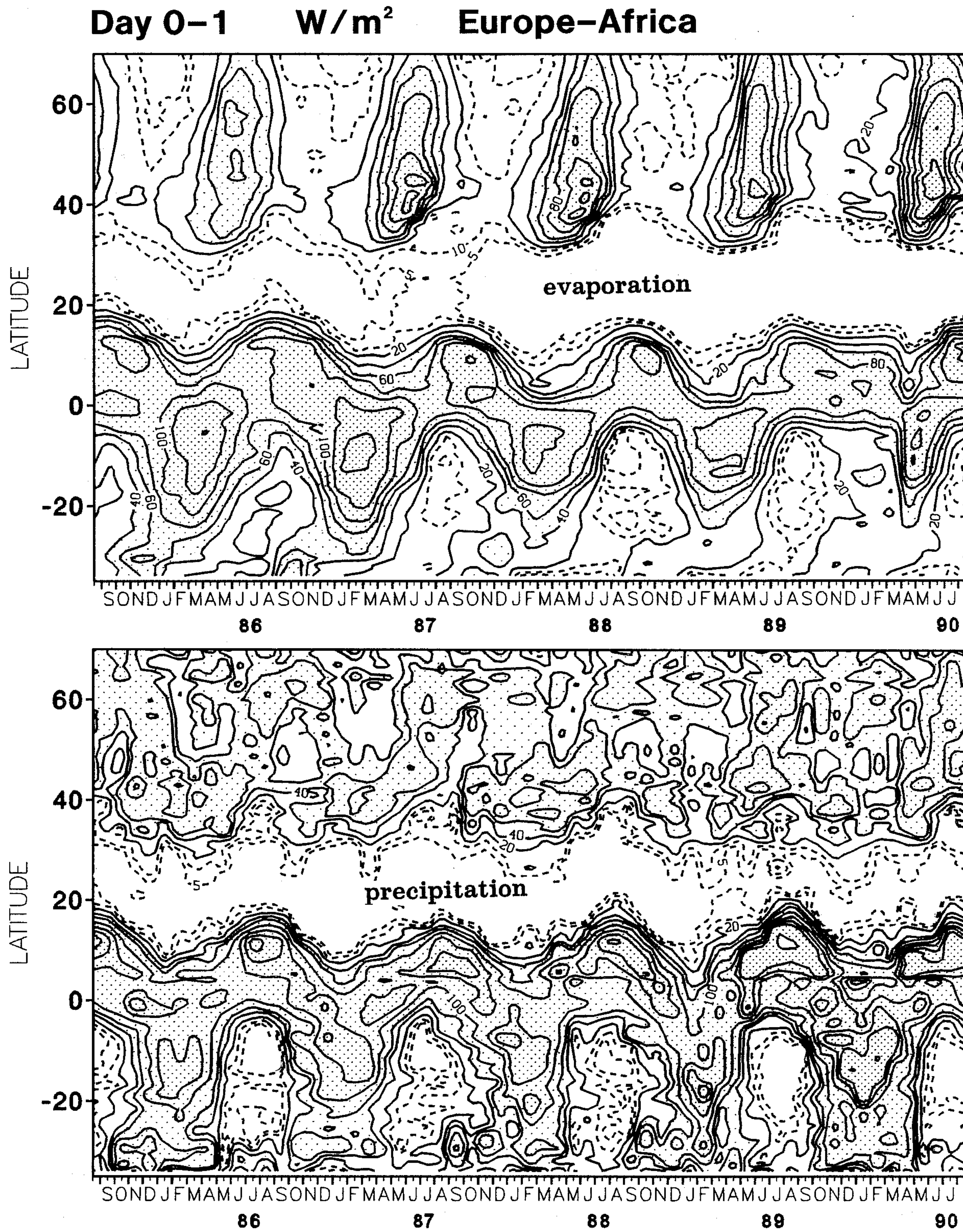

Fig. 11 Latitude-time cross-section of zonal mean latent heat fluxes and total precipitation in the monthly mean day 0-1 forecasts over continental grid points for the section Europe/Africa (20°W - 50°E). Contour interval for latent heat flux: 20 W/m^2; extra dashed contours at 5 and 10 W/m^2. Contours for precipitation at 5, 10, 20, 40, 60, 100, 150, 200, 250 and 300 W/m^2. Contours at 4 and 10 W/m^2 are dashed.

expected to reduce the evaporation over land (Blondin and Böttger, 1987). A steep gradient around March 90 is explained below.

The Sahel zone is clearly indicated in Fig. 11 by a belt with latent heat fluxes and precipitation below 10 W/m^2. This belt widens 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 increase 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. 10), 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 a clear annual cycle 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 behaviour 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. CONCLUSION

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 (day 0-1 means) 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 to 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 values from 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 presently available estimates from satellite measurements. For latent heat fluxes the spin-up is restricted to oceanic areas. Recently this problem has been reduced considerably. The spin-up is especially large where the main observational data sources are satellites but no cure has been found yet.

Over southern hemisphere extra-tropical oceans there is a strong spin-up in the large scale (frontal) precipitation during the first three days of forecast. Short range forecasts most likely underestimate the precipitation amounts. The only available observational data in these areas are those from satellite and it is suspected that these data are used inconsistently in the assimilation scheme leading to too weak large scale rising motion.

For using ECMWF forecast values of precipitation and evaporation as estimates of the truth, different forecasts lengths have been suggested depending on the spin-up characteristics over different areas. Also a fast loss of skill in predicting precipitation with forecast length has to be taken into account. Using day ½-1½ forecast means may be the best compromise for the whole globe.

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.

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 physical 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.

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