USE OF SATELLITE DATA TO VALIDATE THE HYDROLOGICAL CYCLE OF THE ECMWF MODEL

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1. INTRODUCTION

The distribution of observation stations which report precipitation on a regular basis is very much biased towards the Northern Hemisphere land masses, and even there the coverage is far from being uniform. In the tropical areas, which contribute the largest part to the total rainfall, the station density is especially low. For a global validation of the hydrological cycle it is therefore convenient to use measurements from space. The disadvantage of this approach is, that most of the satellite data contains only secondary information about hydrological processes, but no reliable precipitation rates yet.

A widely used quantity for investigating tropical convection is the Outgoing Long wave Radiation at the top of the atmosphere (OLR). Minimum values of OLR give a good indication of the regional distribution and intensity of deep convection. Additional information for the validation of clouds and their albedo is provided by space measurements of net solar radiation at the top of the atmosphere.

This investigation will cover problems of the humidity analysis and forecast errors of parameters which are related to the hydrological cycle. Section 2 contains a discussion of the quality of the humidity analysis. The horizontal and vertical distribution of precipitable water has an important influence on producing realistic rainfall rates in the model. In the following sections radiation measurements from different experiment groups are used to derive conclusions for the intensity of deep convection, cloud properties and surface albedo.

2. PRECIPITABLE WATER

One important condition for a realistic simulation of the hydrological cycle is a reasonable humidity analysis. Illari (1989) has shown that the satellite derived precipitable water content (PWC) has useful information which contributes to an improvement of the humidity analysis. However, the statistical retrieval method to derive PWC from radiance measurements of the TIROS-N Vertical Sounder (TOVS) tends to produce rather smooth spatial and temporal structures which can have a detrimental effect in areas with large horizontal or vertical gradients or during times of rapid changes. Tjemkes and Stephens (1990) have shown that the precipitable water derived from the Special Sensor Microwave /Imager (SSM/I) produces a much higher temporal variance and does not have the zonalization effect seen in the TOVS derived precipitable water. The PWC values available for this study were produced in the Remote Sensing System, Sausalito, California, using a retrieval method described by Wentz et al. (1986).

The comparison between the PWC derived from microwave measurements (SSM/I) with the PWC of the ECMWF forecast and analysis is carried out for July 1990. Forecast experiments suggest that the ECMWF analysis of PWC for this month is more realistic than for previous July months due to a model change in June 1990 in which the surface latent heat flux in low wind speed situations over sea was increased. The disadvantage, however, of selecting a more recent month is that a simultaneous comparison is not possible, the available SSM/I data set extends only to MAY 1990. Therefore a SSM/I based PWC mean of July 1987, 1988 and 1989 (Fig. 1a) compared with PWC in the ECMWF analysis for July 1990 (Fig. 1b). The difference between the SSM/I PWC for the three July months and the ECMWF analysis is shown in Fig. 1c.

In the tropical convergence zone the ECMWF analysis underestimates PWC. The microwave measurements generally exceeds 50 kg/m^2 in this area and 55 kg/m^2 in the Gulf of Bengal, the East Pacific and the extreme West Pacific. Along the tropical convergence zone the ECMWF analysis is drier by around 5 kg/m^2. The differences are particularly large in the Indian Ocean just south of the Equator where the ECMWF analysis is up to 10 kg/m^2 drier.

In the subtropics the opposite picture emerges. The SSM/I analysis is substantially drier in the oceanic trade wind areas. The largest differences are found on the eastern side of the continents where the sea surface temperature is relatively low. Here the ECMWF analysis contains around 10 kg/m^2 more precipitable water. From data assimilation experiments with and without satellite data it is known that the use of TOVS-derived PWC in the humidity analysis is mainly responsible for the moistening of the subtropics.

There are remarkable changes of the PWC in the first 5 days of the forecast. The difference map between the day-5 forecast and the analysis for July 1990 (Fig. 1d) indicates that the model has a general tendency of drying the subtropics and moistening large areas of the tropics where the deep convection occurs. The similarity of the PWC forecast change to the PWC difference between the SSM/I analysis and ECMWF analysis (Fig. 1c) suggests that the model has a tendency to approach a state which agrees more with the SSM/I analysis than with the ECMWF analysis. The forecast changes in the Indian Ocean along the equator are a particularly good example for this. The underestimation of PWC in the ECMWF analysis compared to SSM/I of up to 10 kg/m^2 is almost identical to the increase during the operational forecast by day 5. In this region a remarkable spin up

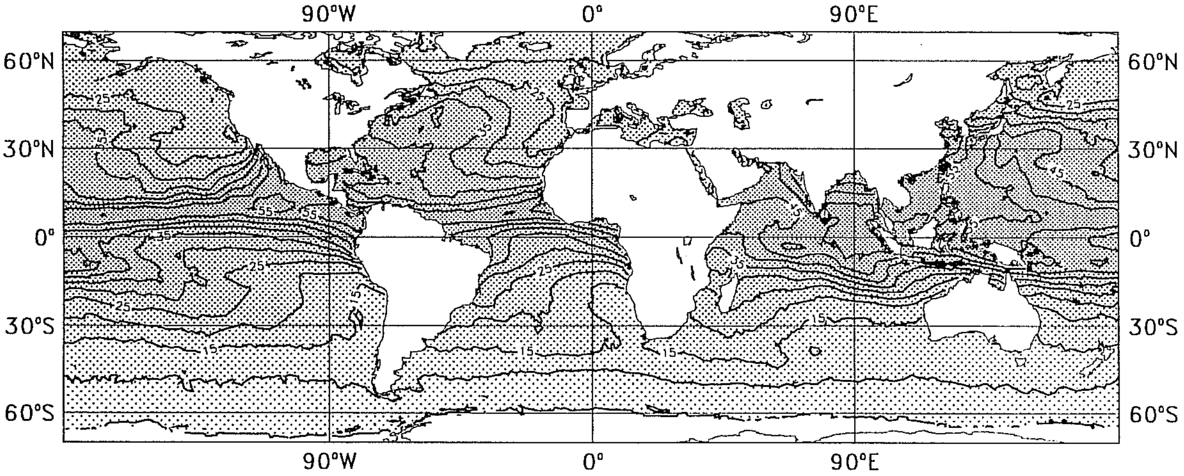

Fig. 1a: PWC derived from SSM/I observations as a mean over July 1987, July 1988 and July 1989. Units: kg/m^2.

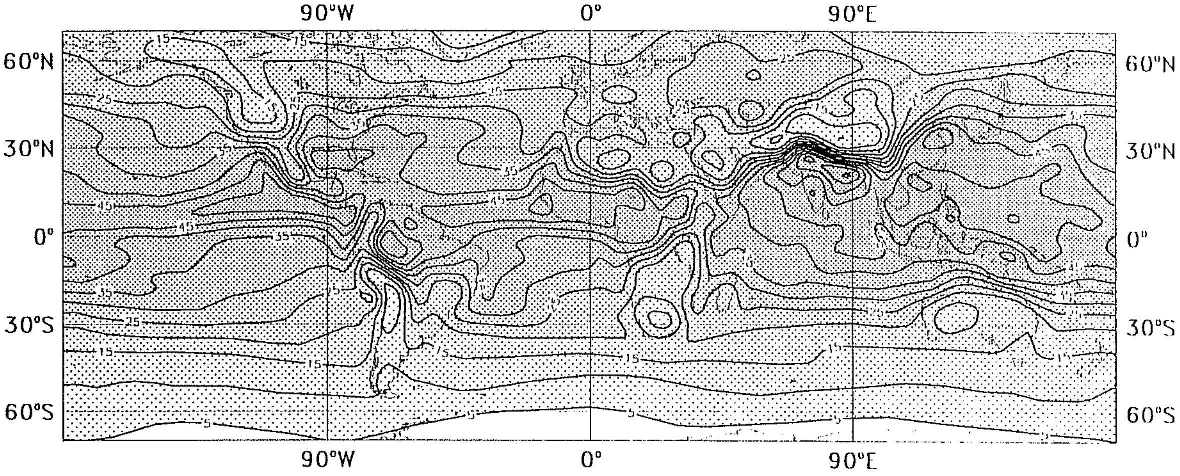

Fig. 1b: Mean PWC of the ECMWF analysis for July 1990. Units: kg/m^2.

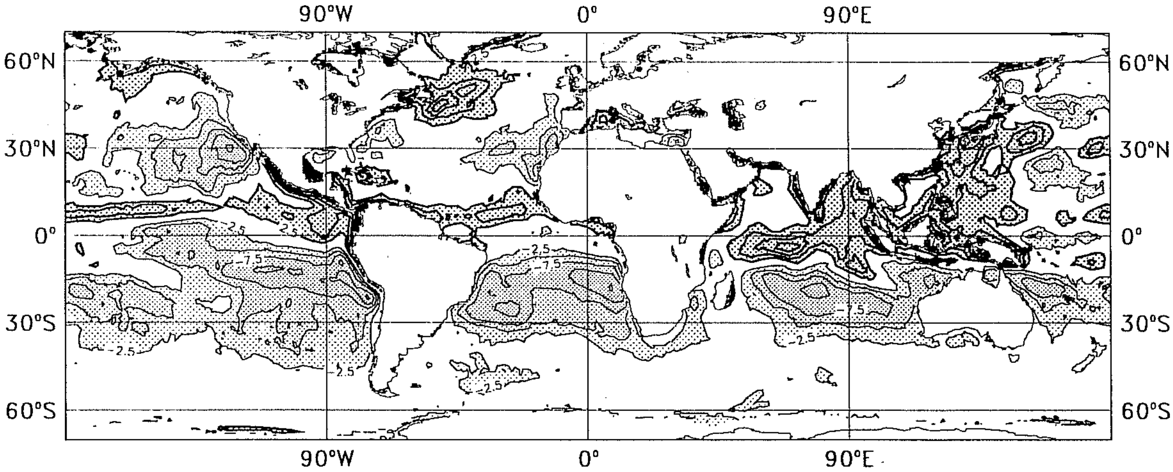

Fig. 1c: Difference between the mean SSM/I derived PWC and the mean ECMWF analysis PWC for July 1990. Units: kg/m^2. Contours: +/-2.5, +/-5.0,...

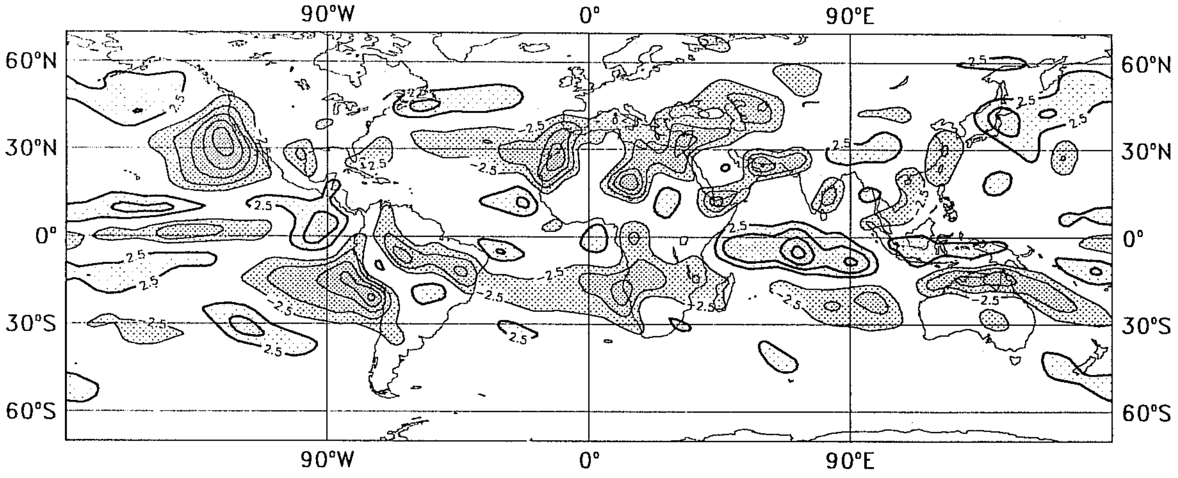

Fig. 1d: Difference between the mean PWC of the 5-day forecast and the analysis for July 1990. Units: kg/m^2. Contours: +/-2.5, +/-5.0,...

of the precipitation occurs during the forecast. The model seems to compensate the deficit of moisture in this area by an increased advection of moisture, which is accompanied by an enhanced precipitation.

3. GREENHOUSE FACTOR

The atmospheric greenhouse effect, which is defined as the amount of long wave radiation trapped in the atmosphere, is dependant on the precipitable water content, the tree dimensional distribution of clouds and their optical properties. The evaluation of the model greenhouse effect can provide useful information about possible errors in the hydrological cycle of the model and their influence on a climate drift in long integrations.

The observed greenhouse effect can be calculated from satellite measurements of OLR and analysed sea surface temperatures (T_s). As the emitted radiation at the surface increases as the fourth power of T_s one would expect the greenhouse effect to increase with increasing surface temperature as well. Here the greenhouse factor

$$g=OLR/I$$

is defined as the ratio between the OLR at he top of the atmosphere and the long-wave radiation emitted from the surface ($I=\sigma T_s^4$). This definition removes the T_s^4 dependence of g in a similar way as the normalized greenhouse effect $g^*=(I-OLR)/I$ used by Raval and Ramanathan (1989).

The calculation of the observed greenhouse factor is based on the NMC SST analysis of July 1985. For OLR at the top of the atmosphere ERBE measurements have been used. The scatter diagram (Fig. 2a) shows the observed greenhouse factor g=OLR/I as a function of the surface temperature at all sea points with a SST of more than 270 K. Over a wide range of surface temperatures the greenhouse factor increases slighltly with T_s. By considering the Clausius-Clapeyron eqation, the increase of g with T_s under clear sky conditions can be explained by the H_2O feedback, as the water vapour content in the atmosphere increases with T_s.

For SST temperatures higher than 299 K the greenhouse factor has a strong nonlinear increase with T_s. This is due to the additional greenhouse effect of convective clouds in the tropical convergence zone. The optical thickness of penetrative convective clouds is very high, therefore the emission of long-wave radiation from the cloud tops is relatively low.

For the comparison of the greenhouse factor in the ECMWF model with observations two sets of model OLR are used. One is extracted from 6 hour forecasts which are run four times per day to

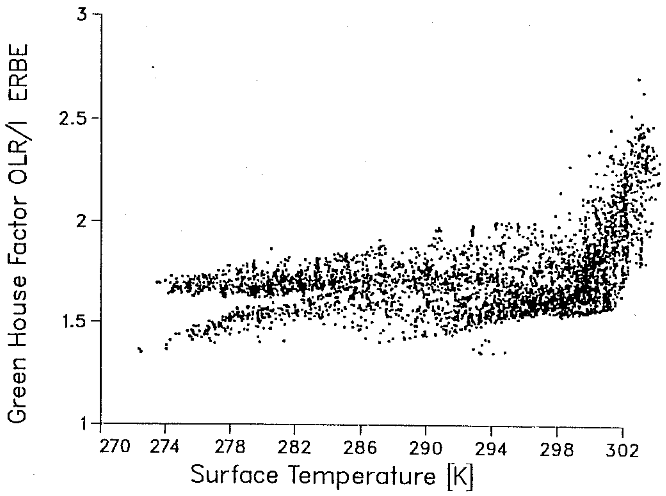

Fig. 2a:
Scatter diagram for the greenhouse factor (definition see text) versus the surface temperature using ERBE data of July 1985 for the OLR.

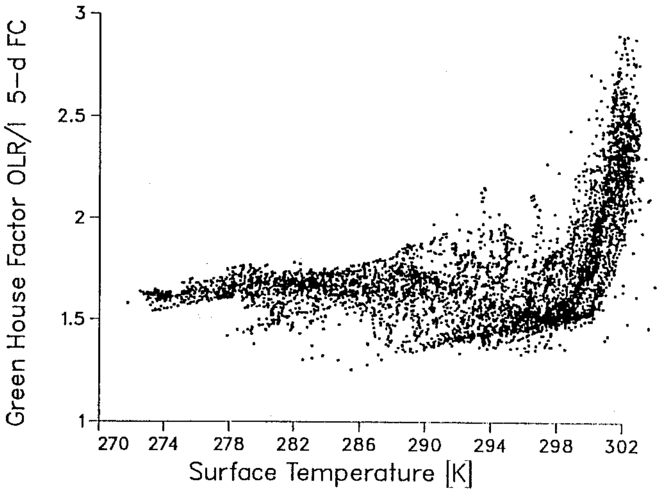

Fig. 2b:
Scatter diagram for the greenhouse factor versus the surface temperature using the 6-hour forecast radiation fluxes of July 1990 for the OLR.

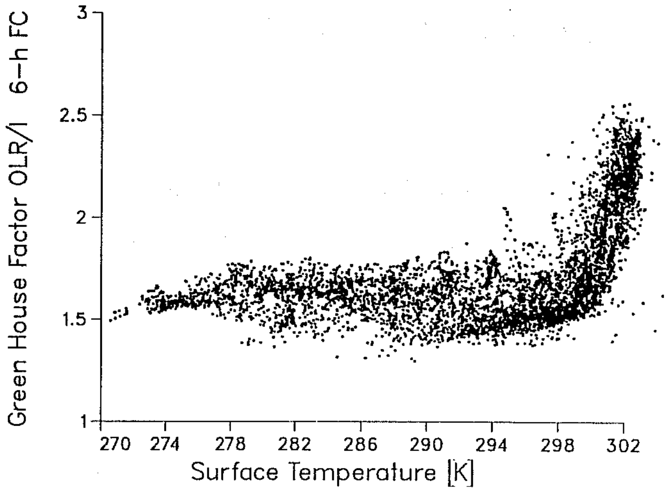

Fig. 2c:
Scatter diagram for the greenhouse factor versus the surface temperature using the 5-day forecast radiation fluxes of July 1990 for the OLR.

produce a first guess for the analysis (Fig. 2b). The second set is calculated from 5-day forecasts and represents the average outgoing long wave radiation for the first five days of the forecast (Fig. 2c). In the comparison one has to take into account that the OLR from ERBE and the appropriate SST are monthly means for July 1985 whereas the model OLR and the corresponding SST are for JULY 1990. Despite the different time periods a reasonable overall agreement between the observed and model simulated greenhouse factor for the 6 hour forecast can be seen. Especially the representation of the cloud forcing at high SST's represents a marked improvement compared to July 1988 (not shown). The new radiation scheme introduced in May 1989 produces a more realistic OLR in the tropical areas of deep convection (Morcrette, 1990). There are, however, noticeable differences which are an indication of model problems.

For a large range of sea surface temperatures (274 - 294 K), the greenhouse effect in the model is smaller than in the observations. The consequence is that in these temperature ranges the slight increase of the greenhouse factor with T_s seen in the observational data set does not seem to be present in the 6-hour forecast.

For temperatures typical for the tropical convergence zone (296 -302 K), the nonlinear increase of the greenhouse factor with T_s is steeper than in the observations. Noticeable is also a positive bias of the greenhouse effect for high SST values in the 6-hour forecast.

A relatively sharp lower limit in the distribution of the greenhouse factor appears for a SST range between 290 and 300 K. This boundary is also present in the 6-hour forecast; however, the minimum values are lower. From maps of the greenhouse factor (not shown) it is clear that the greenhouse effect in the 6-hour forecast is too low in the areas of subtropical highs and particularly on the western coasts of the continents. Though the comparison against SSM/I indicates that the analysed PWC is probably too high in the subtropical highs which would increase the greenhouse effect, the obtained underestimation suggests that the lack of low level cloud cover has a far greater influence.

For a forecast range of 5 days the greenhouse factor distribution against the SST shows some changes compared to the 6-hour forecast distribution. The nonlinear increase in the 5-day forecast is as steep as in the 6-hour forecast, but the positive bias of the greenhouse factor compared to observation is even larger than for the 6-hour forecast. In a temperature range between 290 and 298 K a larger spread of points in the forecast distribution points to an increase of cloud cover compared to the first guess. This tendency is continuing up to the day-10 forecast (not shown).

4. NET RADIATION FLUXES AT THE TOP OF THE ATMOSPHERE

The available ERBE data sets which contain the net radiation fluxes at the top of the atmosphere for selected summer and winter months have become an important part of the model verification at ECMWF. The comparison of observed and model radiation fluxes provides useful information about possible errors in the radiation scheme, in the parametrization of convection, in the representation of clouds and for problems of the albedo. Additionally long wave outgoing radiation data published as monthly mean values in the Climate Bulletin by NOAA which are based on the NOAA 11 AVHRR IR window channel measurements offer the possibility of a simultaneous comparison.

4.1 Outgoing long wave radiation in the tropics

The outgoing long wave radiation at the top of the atmosphere (OLR) is widely used to identify the intensity and area coverage of deep convection in the tropics. Fig. 3a shows the observed ERBE OLR for July 1985, Fig. 3b the model OLR for the first 6 hours of the forecast averaged over 4 forecast per day, and Fig. 3c shows the difference between the two.

In the observed and model produced radiation fluxes for July the ITCZ is well defined as a minimum of OLR north of the equator for most regions. Along the ITCZ the OLR values in the 6-hour forecast are generally lower than in the ERBE observations. The observed OLR suggests that the maximum convective activity over the West and East Pacific is separated by a region around 140 degrees west with substantially reduced convection. In contrast to observation the 6-hour forecast produces a fairly uniform band of OLR over the Pacific ITCZ. Similarly the 6-hour forecast OLR seems to be too low in the ITCZ of the western Atlantic. In the Indian and East Asian monsoon area the tendency to lower OLR values in the forecast than in the observation is less pronounced. Further regions with large differences are the western Part of the Indian Ocean and the region east of New Guinea.

The similarity between the ERBE OLR of July 1985 and NOAA 11 OLR of July 1990 (not shown) confirms that the inter-annual variation of OLR in most regions is fairly low. However, over the Indian Ocean the simultaneous NOAA 11 observations for July 1990 show lower values than ERBE measurements. It seems that in this area the model bias against ERBE data from July 1985 is at least partly due to an inter-annual variation.

Over the tropical land areas too low predicted OLR values are found in connection with higher terrain, such as the mountains of Ethiopia and Mexico, and the Atlas Mountains in North Africa. These differences point to excessive convective rainfall over mountains. The operational verification of model rainfall against station data over the Alpine region in summer suggests the same. Also over the Amazon basin in central parts of Brazil does the OLR difference indicate excessive convective rainfall.

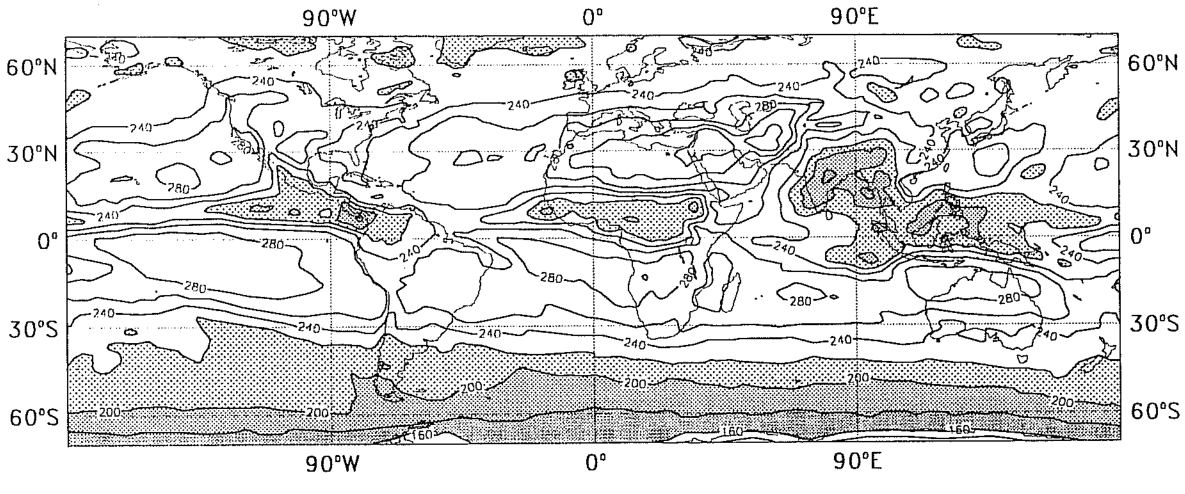

Fig. 3a: OLR from ERBE measurements for July 1985. Units: W/m^2.

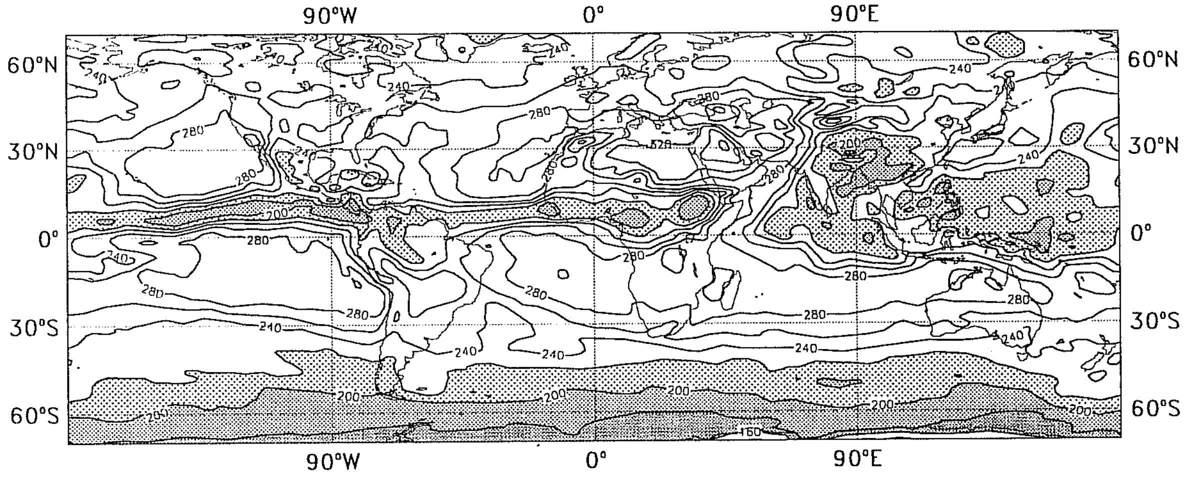

Fig. 3b: OLR of the 6-hour forecast for July 1990. Units: W/m^2.

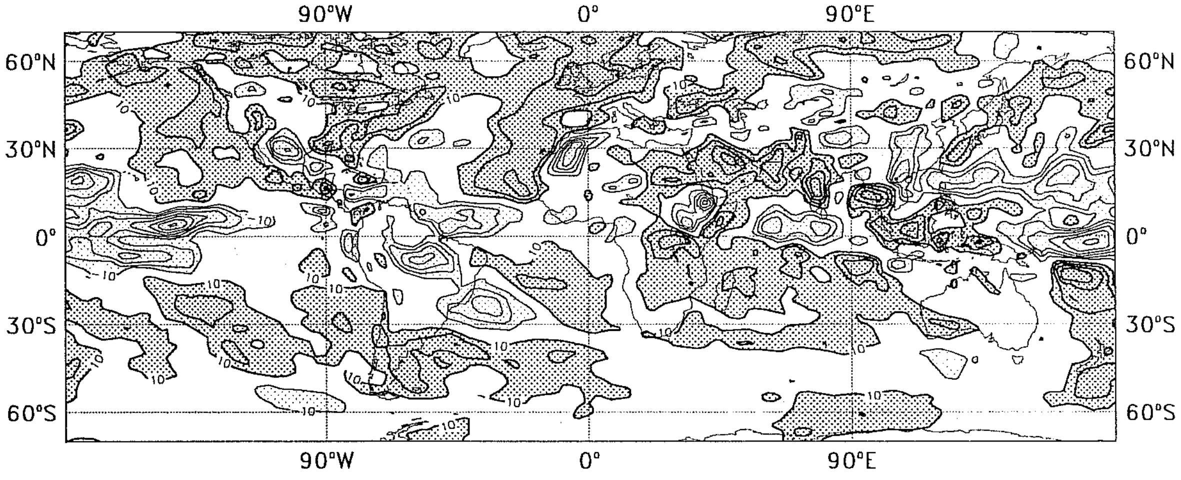

Fig. 3c: Difference between the 6-hour forecast OLR for July 1990 and the observed (ERBE) OLR for July 1985. Units: W/m^2. Contours: +/-10,+/-20,...

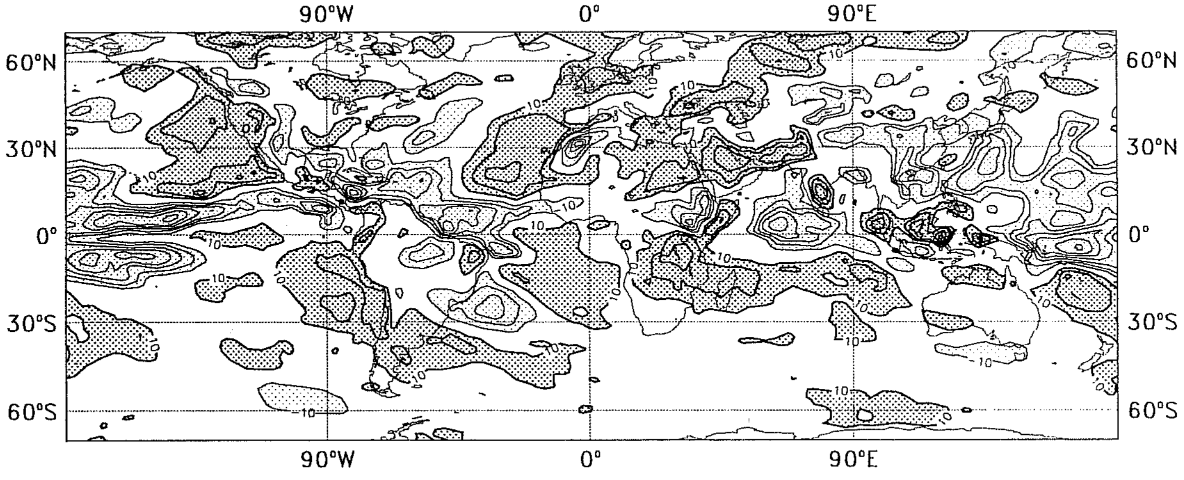

Fig. 3d: Difference between the 5-day forecast OLR for July 1990 and the observed (ERBE) OLR for July 1985. Units: W/m^2. Contours: +/-10,+/-20,...

During the first 5 days of the forecast there is a further decrease of the model OLR in the tropics compared to the first 6 hours as can be seen from the difference between the model OLR and ERBE observation (Fig. 3d). This process shifts the model OLR even more away from the observation than the short range forecast. The decrease of the OLR in the model is particular evident in the West Pacific where values go down to 180 Watts/m^2 compared to 220 or 200 Watts/m^2 in the ERBE observations. But also west of New Guinea the model OLR seems to indicate a further intensification of convection.

4.2 Outgoing long wave radiation in the extra-tropics

Too high values of OLR are found over large parts of the oceans indicating a general lack of cloud cover. This is particularly the case in the high pressure areas on the west coast of the continents. Over the Northern Hemisphere land mass there are some areas with a positive bias. This is, however, a noticeable improvement on the differences in July 1989 when the major parts of the Northern Hemisphere continents showed an overestimation of OLR in the model. This large positive bias in July 1989 was related to insufficient cloud cover and to a too dry soil. Both problems were alleviated by model changes in 1990.

4.3 Short wave radiation in the tropics

For the verification of the short wave radiation fluxes at the top of the atmosphere we use again the ERBE measurements for July 1985. In general the difference between the model fluxes for July 1990 and ERBE radiation fluxes (Fig. 4a) in the solar spectrum at the top of the atmosphere is similar to the differences in the thermal spectrum which results in a certain amount of compensation between errors of the two radiation components. The magnitude of the bias in the short wave radiation is however noticeably larger than in the OLR.

In the tropical convergence zone the solar radiation at the top of the atmosphere is generally underestimated which suggests that the tropical clouds are reflecting too much solar radiation back into space. From the underestimation of OLR in the same areas we had concluded that excessive convective activity could be the reason for this bias.

The change of the radiation bias as one goes from the 6 hour forecast to the 5 day forecast (Fig. 4b) indicates that the reflectivity of the model atmosphere in the tropics is drifting further away from the observations with increasing forecast time. In most tropical areas this corresponds to an increase of convective precipitation. However, in some regions like the western Pacific the decrease of the net solar radiation with forecast time is taking place even with a decrease of rainfall.

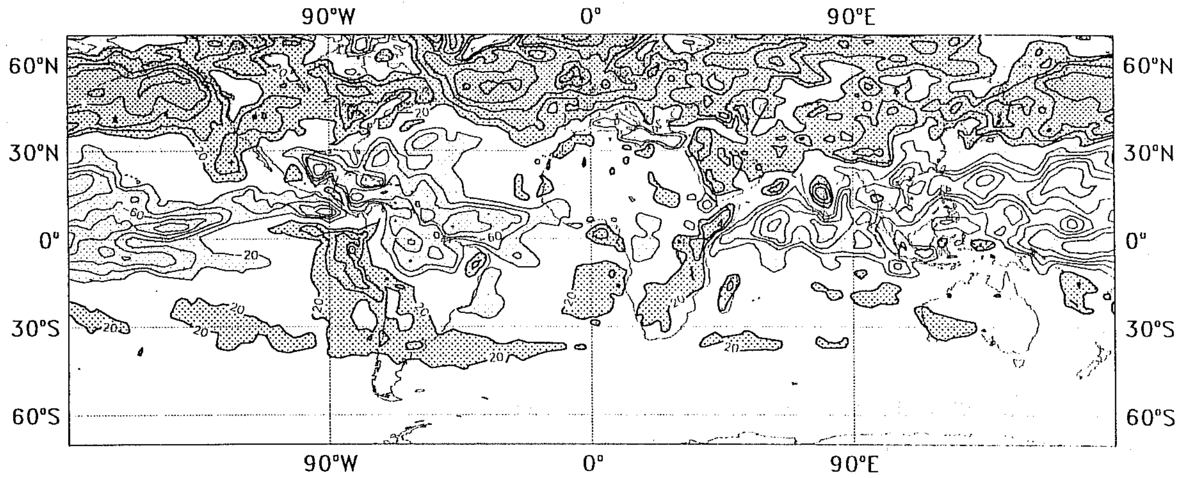

Fig. 4a: Difference between the 6-hour forecast short wave radiation at the top of the atmosphere for July 1990 and ERBE observation for July 1985. Units: W/m^2. Contours: +/-20,+/-40,....

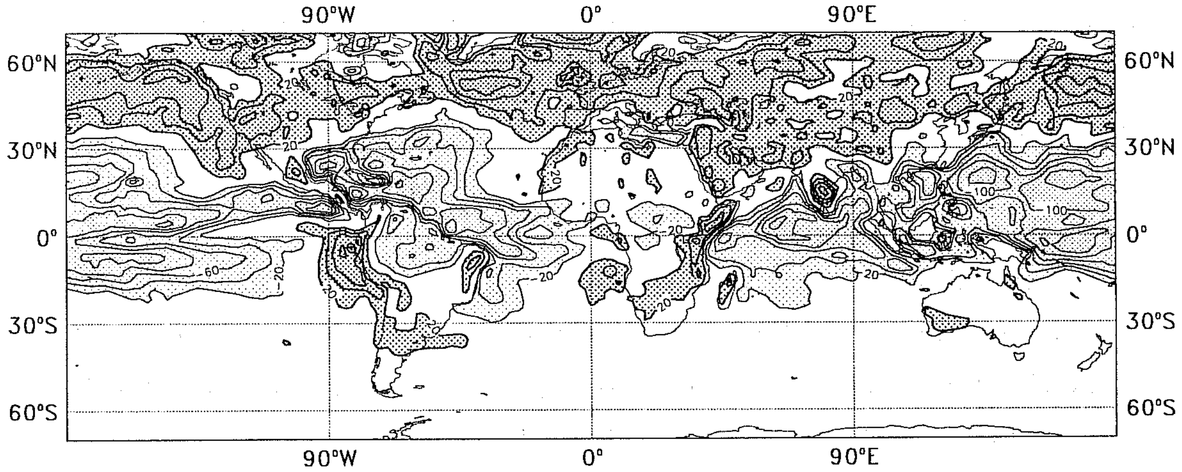

Fig. 4b: Difference between the 5-day forecast short wave radiation at the top of the atmosphere for July 1990 and ERBE observation for July 1985. Units: W/m^2. Contours: +/-20,+/-40,....

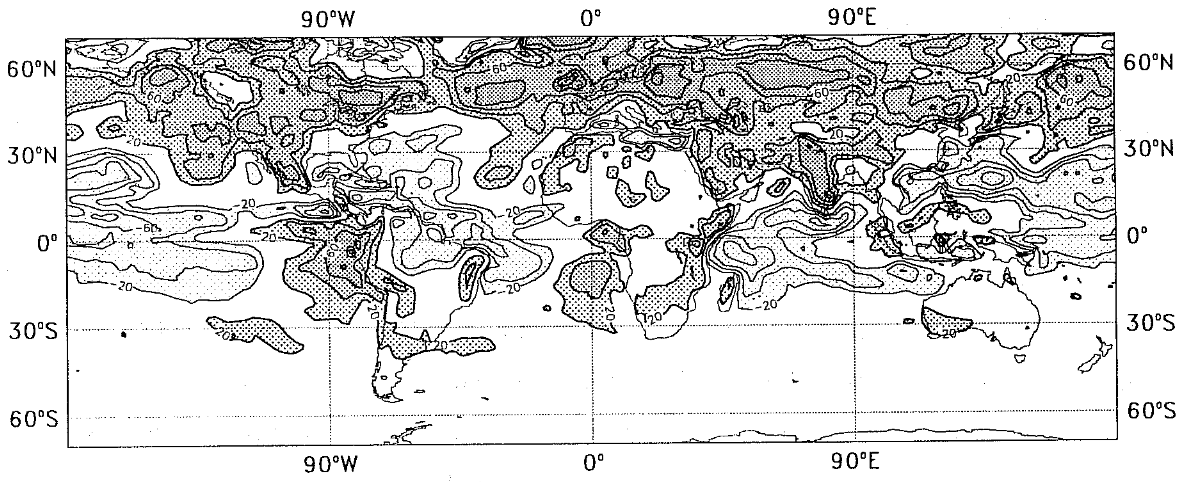

Fig. 4c: Difference between the 5-day forecast short wave radiation at the top of the atmosphere for July 1989 and ERBE observation for July 1985. Units: W/m^2. Contours: +/-20,+/-40,....

For an explanation of this behaviour two model problems are worth considering. First of all, the model has the tendency to moisten parts of the upper tropical troposphere which tends to increase the cloud cover. The availability of the total moisture content in the atmosphere seems to be important for this effect. The increase of moisture supply in low wind speed situations over sea due to the model change in June 1990 has contributed to an increase of the short wave radiation bias in most tropical regions. A second effect can be expected from the model deficiency to warm the upper tropical troposphere. As the cloud liquid water content is estimated from the saturation mixing ratio this temperature error increases the assumed optical thickness of the clouds.

4.4 Short wave radiation in the extra-tropics

Over the non-convective oceanic areas the bias of the model net short wave radiation at the top of the atmosphere is generally positive. This can be explained by lack of cloud cover in most areas which results in a too large absorption of short wave radiation in the sea.

Over the northern hemisphere land areas a predominant positive model bias suggests a similar problem of insufficient cloud cover. However, here the error analysis is complicated by possible errors in the surface albedo. The use of a constant surface albedo in the model throughout the year underestimates the surface albedo in July. With a model change in May 1990 the run-off of convective rain has been reduced. The resulting increase of soil moisture in July 1990 compared to July 1989 has slightly reduced the positive solar radiation bias of the model.

4.5 Net radiation in the tropics

As shown in the previous paragraph, the bias in the short wave part of the spectrum is the dominant bias. Therefore the 6-hour forecast bias in the net radiation (Fig. 5) has almost the same horizontal distribution as the bias in the short wave spectrum.

In the tropics the model bias in the net radiation is characterized by negative values in the areas of deep convection in which high level cloud is generated. In the discussion of the solar radiation it was suspected that too strong convection and problems in the optical properties of the clouds could be the reason. A further estimate of errors related to convection can be gained by investigating the model budget for sensible heat from intial model tendencies (Klinker and Sardeshmukh, 1987). A residual for the sensible heat

$$R_S=-\delta D_S+\delta S_0+L\delta P+(\delta R_T-\delta R_0) \tag{1}$$

can arise from errors in the adiabatic tendencies (D_s), the surface flux of sensible heat (S_0), the condensational heating (LP), and from errors in the net radiation of the atmosphere (R_T-R_0).

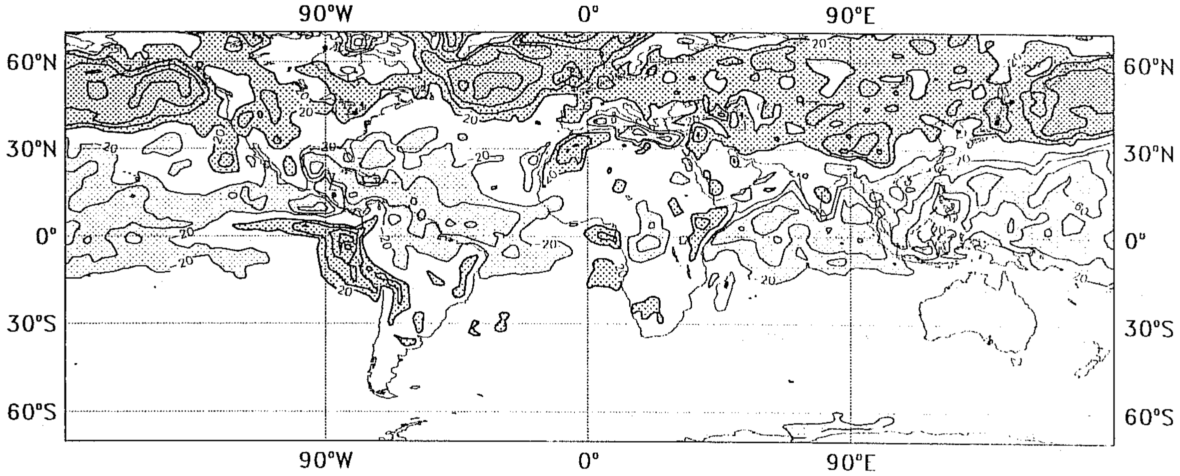

Fig. 5: Difference between the 6-hour forecast net radiation at the top of the atmosphere for July 1990 and ERBE observation for July 1985. Units: W/m^2. Contours: +/-20,+/-40,....

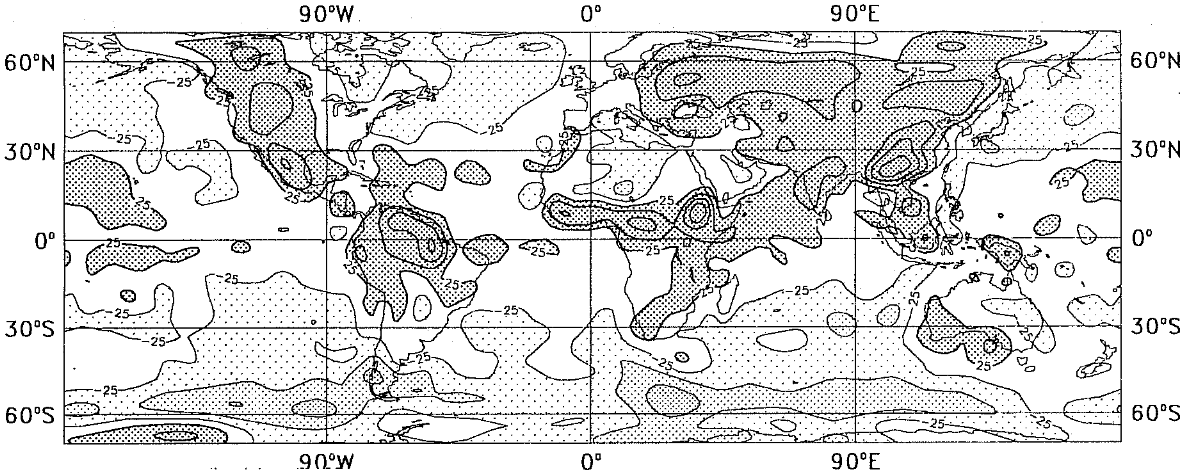

Fig. 6: Budget residual for the sensible heat. Units: W/m^2. Contours: +/-25, +/-75,....

In the tropics a general positive budget residual seems to indicate that the condensational heating is too large (Fig. 6). This is almost certainly true over the tropical land areas where deep convection occurs and the residual is rather large. A residual of up to 175 W/m^2 is unlikely to be related to an error in the net radiation or the surface flux of sensible heat. However over the tropical oceans we cannot be sure as the budget residual is only up to 25 W/m^2. That we get a budget residual here at all is however still a sign of model problems, as the amount of observational data available to the analysis system over the ocean is fairly low compared to land areas.

4.6 Net radiation in the extra-tropics

Over the Northern Hemisphere the net radiation at the top is generally too large compared to observation. Over land the bias is in the order of 30 W/m^2 and maximum values up to 50 W/m^2. The largest differences are found over the Northern Hemisphere oceans, where a lack of cloud cover seems to be responsible for the large overestimation of the net radiation at the top of the atmosphere by up to 70 W/m^2. Support for this conclusion can be obtained from the model's heat budget. In the Northern Hemisphere storm tracks a negative residual in the vertically integrated sensible heat and a positive residual in the latent heat (not shown) indicates insufficient large scale rainfall rates. The radiation bias at day-5 of the forecast suggests that the cloud cover and therefore the large scale rain is still underestimated in the medium forecast range.

At this point it is important to clarify whether the excess of the net radiation at the top of the atmosphere in the model contributes to a large radiative warming of the atmosphere or whether an excessive heating of the model surface is found. For the investigation of this question an estimate of surface net radiation (SRB) from Langley Research Centre is used which represents an average of calculations from seven experimental groups. The RMS differences between the seven estimates indicates that some caution is needed to use this data. A second problem is that similar to the comparison with ERBE data we do not have a simultaneous data set for July 1990, but rather a data set which is valid for July 1983.

Despite these shortcomings the comparison between the SRB net radiation at the surface and the model values turned out to be very useful. The difference map between the two (Fig. 7) has a horizontal structure which is very similar to the difference between ERBE and the model top net radiation. Also the magnitude of the model deviation form the SRB data set is similar. This results suggests that the error in the net radiative cooling of the atmosphere is generally small compared to the errors at the surface. Therefore the radiation bias over the ocean has to a first order only a diagnostic value in that it indicates that there is not enough cloud cover at high latitudes. No interaction between the sea surface temperature and radiation is allowed and the effect would be small in the medium forecast

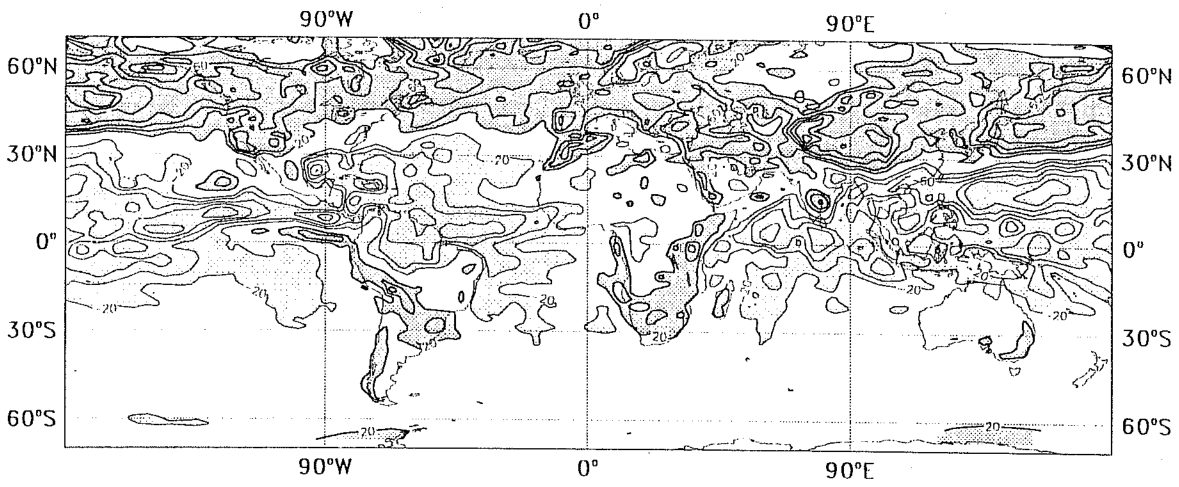

Fig. 7: Difference between the 6-hour forecast net radiation at the surface for July 1990 and the SRB estimate for July 1983. Units: W/m^2. Contours: +/-20,+/-40,....

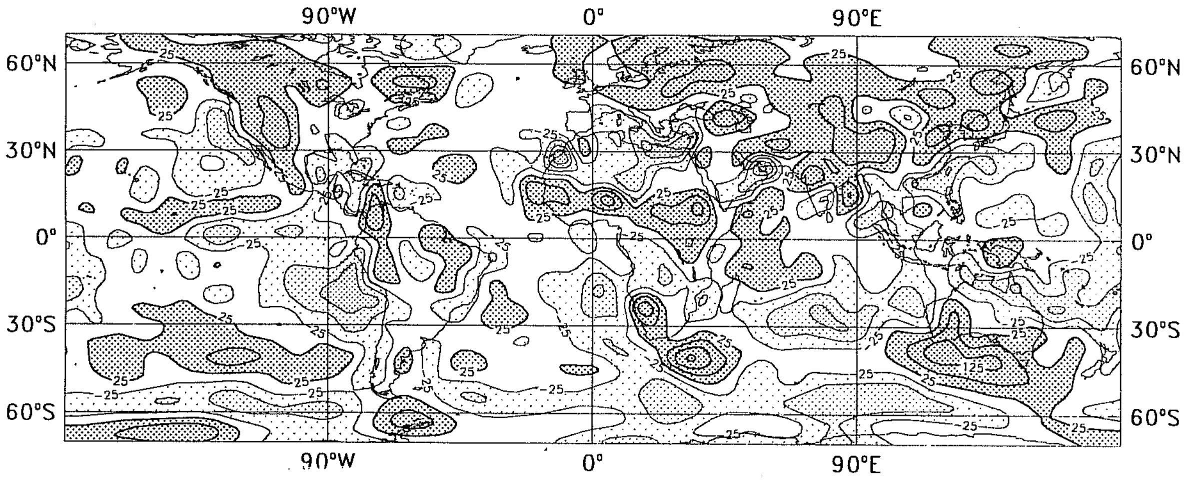

Fig. 8: Budget residual for the sum of the sensible heat and the latent heat. Units: W/m^2 Contours: +/-25, +/-75,....

range of a few days. Over land the net surface radiation is balanced by the surface fluxes of sensible and latent heat and a rather small term of heat flux into the soil. An excessive surface radiation over land has therefore the main consequences of producing too large surface fluxes of heat.

Here it seems to be useful to incorporate again the model budget calculations into the investigation. By integrating the monthly mean tendency of the total heat over the full model atmosphere we obtain, apart from a negligible storage term, a residual for the total heat

$$R=-\delta D+\delta S_0+\delta E_0+(\delta R_T-\delta R_0) \tag{1}$$

which can arise from errors in the adiabatic tendencies (D), the surface fluxes of sensible heat (S_0) and surface flux of latent heat (E_0) and from errors in the net radiation of the atmosphere (R_T-R_0).

The vertically integrated budget for the total heat (Fig. 8) shows a positive residual over large parts of the Northern Hemisphere land areas which reaches up to 75 W/m^2. As we can assume from the result of the comparison of radiation against observation that the radiation error of the atmosphere is rather small, we can conclude that the surface fluxes of total heat over land are too large. The largest residual is found over the Rocky Mountains and over the Himalayas, in both regions the difference between model and SRB data was also especially large. It seems therefore that the problems of the surface heat flux over land are enhanced over high terrain.

5. DISCUSSION

Comparing radiation fluxes measured from satellite with model produced fluxes turned out be very useful for the validation of the hydrological cycle of the ECMWF model. The underestimation of the model OLR and short wave radiation at the top of the atmosphere in the tropics suggests that the convective activity in the model is too strong. Though errors in the optical properties of convective clouds may contribute in parts to the radiation bias, two further independent estimates of errors in the convective activity suggest an overestimation as well. The calculation of the vertically integrated heat budget from initial model tendencies reveals a large positive residual over tropical land areas which seems to be related to excessive condensational heating. Furthermore a verification of model precipitation over Europe, which is done on a operational basis at ECMWF indicates that the model rainfall represents an overestimation in the summer months when most of rain is of convective nature.

If the deep convection as a branch of the Hadley Circulation represents an overestimate as these results suggests, then the tendency of the model to dry the subtropics and moisten the tropics in the ITCZ is plausible. In the short range forecast the drying of the subtropics can be seen as a correction of a positive bias in the humidity analysis. The use of PWC derived from TOVS in the humidity analysis produces a moistening of large parts of the subtropics. However, the continuing drying process during the medium range forecast produces too dry conditions in parts of the subtropics, especially at the west coast of the continents.

The combined use of observed net fluxes at the top of the atmosphere (ERBE) and at the surface (SRB) indicate that the net atmospheric radiation error is probably small compared to errors at the boundaries. The largest problems arise from the surface radiation bias over land. Here the overestimation of net solar radiation fluxes is due to insufficient cloud cover and a too low surface albedo. The balance between all fluxes at the surface produces an overestimate of the surface heat fluxes. This problem is further enhanced over mountains.

A overestimation of the net solar radiation fluxes over the oceanic storm tracks points to a lack of cloud cover here as well. A corresponding underestimation of large scale rainfall can be deduced from the heat budget.

Recent model changes have contributed to a noticeable alleviation of the model problems found in this investigation. The combined effect of the new surface albedo and the change to maximum cloud overlap has decreased the convective rainfall over land and brought the net radiation fluxes of the model closer to observation.

6. ACKNOWLEDGEMENTS

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