VALIDATION OF RADIATION AND CLOUDS

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1. INTRODUCTION

The necessity to properly validate the parametrization of radiation and clouds in numerical weather prediction models is a natural consequence of their importance for the success of the forecast. The importance of these processes was never questioned in the context of climate simulations. In such simulations, and of course also in the real atmosphere, the spatial and temporal distribution of sources and sinks of radiative energy determines to a large extent the evolution and mean state of the earth-atmosphere-system.

However, until some ten years ago, the parametrization of radiative transfer and clouds in NWP models was considered to be a low priority subject. The use of rather crude parametrization schemes (e.g. Newtonian cooling, climatological fluxes and heating rates, etc.) was supported by several arguments. First of all, this negligence of radiative processes reflected the fact, that the quality of the model forecast of the synoptic flow in the first days of the integration was not very sensitive to the radiative forcing. In addition, the extreme computational requirements of a detailed description of the radiative transfer process constitute a large obstacle to the implementation of sophisticated schemes in operational NWP models, which are subject to rather severe time constraints. This fact implies that highly approximative methods have to be used in order to comply with the operational schedule. The severity of the approximations is to some extent dictated by the capabilities of the available computer system and the progress in computer science has alleviated this problem to some extent. However, even with the most modern computer a straightforward solution of the radiative transfer equation is far too expensive for use in NWP models.

The fact that earlier NWP models paid little attention to the parametrization of radiative transfer is also related to the rather limited scope of these models with regard to useful forecast range and the number and kind of useful forecast products. It is mainly a consequence of the extension of the useful forecast range that the proper parametrization of physical processes in general, and radiative transfer in particular, are now considered as essential for further progress in NWP. Furthermore, the increasing range of forecast products, including point predictions of weather elements (e.g. near surface temperature, cloud cover, precipitation), requires an accurate representation of those processes which control the evolution of these quantities. Radiation, and of course also other diabatic processes, affect such variables (e.g. via the diurnal cycle or cloud radiation interaction) and thereby the forecast quality from the very beginning of the integration.

Based on these arguments it was decided at the DWD that there is no reason to employ basically different radiative transfer schemes in the various components of our NWP system. The present operational system of the DWD consists of a global model, based largely on an earlier version of the ECMWF spectral model, and a high resolution limited area model covering mainly Europe and a large part of the north atlantic region. Since a number of the results presented in the following sections were produced with two versions of this global, a description of the most important differences between our version and the ECMWF model will be provided. In contrast to the envelope orography used at ECMWF, a mean orography is employed in our model in order to be more consistent with the limited area model of DWD, which obtains it's boundary values from the global model. Furthermore, the horizontal and vertical resolution corresponds to the earlier ECMWF configuration of T106L19, rather than the present ECMWF configuration of T213L31. In the area of physical parametrization we used originally the ECMWF cycle 34 parametrization schemes without any modification. However, in September 1991 we replaced the ECMWF radiation scheme (cf. *Morcrette*, 1990) by a scheme developed in cooperation with the French National Meteorological Service (cf. *Ritter and Geleyn*, 1992, in the following abbreviated as RG92). In contrast to the ECMWF scheme, which employs an emissivity-type method in the thermal spectral domain, the DWD is based on the δ-two-stream formulation of the radiative transfer equation throughout the spectrum. Other discrepancies between the two schemes, which will be discussed in more detail in the following sections, result mostly from differences in the underlying optical properties of the various optically active atmospheric constituents. Minor differences may also result from the inclusion (in the DWD scheme) respectively exclusion (in the ECMWF scheme) of minor trace gases (CH_4 and N_2O) and a detailed aerosol model. For details of the DWD radiation scheme the reader is referred to the paper by Ritter and Geleyn.

In the following sections the subject of validation of radiation and clouds will be discussed mostly from the radiative point of view. However, since there is a strong interaction between clouds and radiation, there is no real separation between the two issues. In analogy to the step by step validation of any new parametrization scheme we will look in the next section at those aspects of radiative transfer that can be judged outside of the framework of the host atmospheric model. This is followed by a discussion of the so-called on-line validation, i.e. methods, results and problems that are relevant when the parametrization scheme interacts with all the other components of the host model. This section is split in one part, where classical validation methods are described, and a second part, where new concepts and approaches are discussed.

2. OFF-LINE VALIDATION OF RADIATION SCHEMES: CONCEPTS AND RESULTS

Any parametrization scheme that is considered for implementation in an atmospheric model ought to be validated independent of an interaction with other model components as far as possible. Even though a positive impression resulting from an off-line validation study does not guarantee that the scheme will also succeed as a module in the more or less complex environment of the host model, several extremely important aspects can be addressed. The elimination of coding errors is a trivial but nevertheless important purpose of testing any parametrization scheme on its own. Equally important is the building up of confidence in the capabilities of the scheme. Since almost any parametrization scheme employs approximations, the off-line validation of the scheme provides the opportunity to investigate in detail the penalties associated with such approximations in comparison to the results obtained from the original relations. However, a conclusive judgement about the quality of the agreement or disagreement at this stage of the validation process is not possible, since the magnitude of deviations has to be seen in relation to their impact in the host model. Another purpose of this type of validation exercise is the detection of sensitive aspects of the scheme. Since most parametrization schemes are designed as a replacement of an existing module, major differences found in a comparison of the two schemes as applied to a common atmospheric situation indicate also potential sources of discrepancies when the results are compared from complete integrations of the atmospheric model.

A preliminary impression about the validity of a certain approach can often be gained by pure deliberation. Before a single line of code has been written, the overall potential and limitations of a scheme may be known from a thorough assessment of the assumptions involved in it's design. As an example let's look at the issue of emissivity approach versus δ-two-stream method in the solution of the radiative transfer problem in the thermal spectral region. The typical way to alleviate the disability of emissivity schemes to consider explicitly the effects of scattering on the radiative fluxes and heating rates is to attribute a so-called effective emittance as optical property to the clouds. This emittance, which in most schemes of this kind is formulated as an empirical function of the cloud liquid water content, is an enhancement of the pure emissivity as it would result from a spectral integration of cloud droplet absorptive properties. This enhancement should account for the fact that the reflection of photons directed towards the cloud will contribute to the flux directed from the cloud, thus increasing the flux beyond the value that would occur if only pure emission, absorption and transmission were considered. The limitations of this approach are clearly illustrated in Fig.1, taken from *Stephens* (1980). Illustrated is the downward effective emittance, calculated as the ratio of the downward flux and the black body flux at the cloud boundary, as function of optical depth for a cirrus cloud located in different atmospheric environments. As is to be expected, and could be simulated in an emissivity type scheme, the effective emittance is a monotonic function of optical depth. The dependence of the effective emittance on the atmospheric environment results from the fact that the optical properties of the cloud operate on incoming fluxes of different magnitude in the various atmospheres. Differences in upward fluxes at the lower cloud boundary are to a large extent caused by differences in surface temperature and atmospheric water content. A parametrization of effective emittance as function of cloud liquid water content is not capable to take this effect into account and it is extremely unlikely that any extension of this basic concept will be adequate for the purpose. A similar conclusion can be derived from results of the ICRCCM

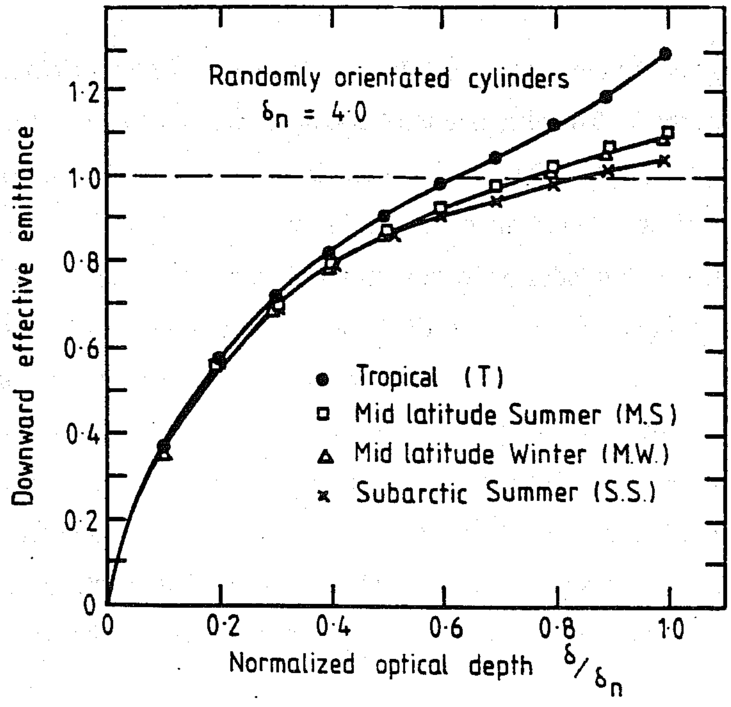

Fig.1: Downward effective emmitance as a function of optical depth of a cirrus cloud located in four different model atmospheres (from Stephens, 1980)

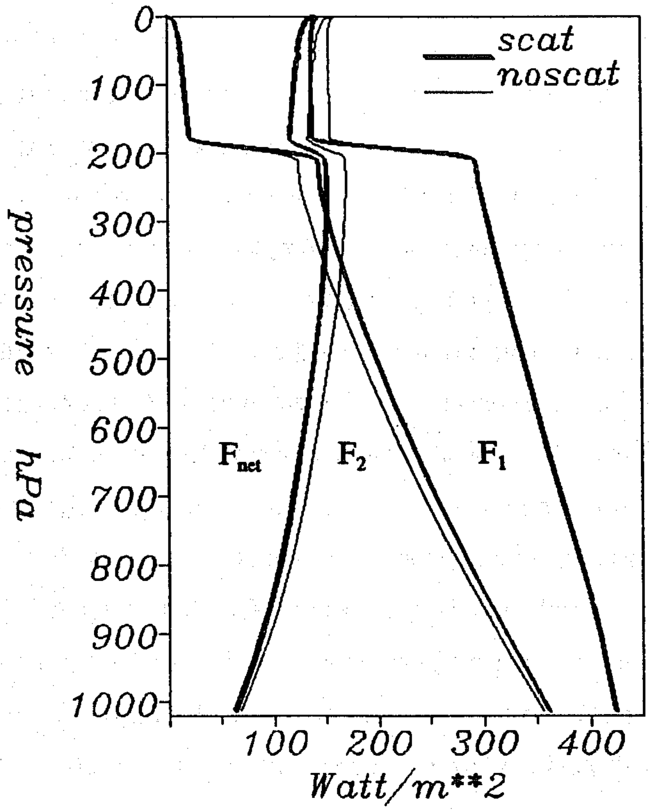

Fig.2: Upward (F_1), downward (F_2) and net thermal flux calculated with the radiation scheme of Ritter and Geleyn (1992) for midlatitude summer conditions. Scattering by droplets in a high cloud is either considered (thin lines) or neglected (thick lines). The cloud specifications conform to the type CS/10 in the ICRCCM project (cf. Table 1 of Ellingson and Fouquart, 1990)

project, presented in Table 1 of *Ellingson and Fouquart* (1990). A change of 35 W/m^2 in the net thermal flux at the tropopause is documented as the result of change in the drop size distribution, while the liquid water content was kept constant. This effect is a consequence of the impact of drop size on the scattering efficiency.

The relative importance of scattering processes in the transfer of thermal radiation is demonstrated in Fig.2. For a cloud located in the upper troposphere of a midlatitude summer atmosphere a calculation with the DWD radiation scheme excluding scattering (thin lines) leads to radiative fluxes which are quite different from the calculation when scattering is included (thick lines). The impact is particularly notable in the OLR, which changes by approximately 20 W/m^2.

A comparison of the parametrization to reference calculations is a common component of the off-line validation exercise. Apart from a comparison of fluxes and heating rates, it is often equally important to look at some more specific aspects of the scheme. In the DWD radiation scheme a whole sequence of fitting algorithms (cf. RG92) is required for the description of the broadband gaseous transmission functions. A thorough examination of the quality of each individual step and of the final result is obviously essential in order to check the validity of this approach. In the first step of the approximation the transmission function calculated by a band model at a given combination of reference temperature and pressure is fitted by a series of decaying exponentials. The quality of this fit is largely a function of the number of the development terms. A small number of terms is desirable, since the computational requirements of the radiative transfer scheme are strongly related to this number (cf. RG92). The variation of the gaseous transmission as a function of pressure and temperature is taken into account by the application of two further fitting algorithms, which provide corresponding scaling coefficients for each individual coefficient of the exponential fit. The validity of this concept is illustrated in Fig.3. The transmission function for water vapour in one of the spectral intervals of the DWD radiation scheme at a temperature/pressure combination which is quite different from the chosen reference conditions is fitted extremely well by the approximation. A third curve indicates the poor fit that would be obtained, if pressure and temperature scaling coefficients were simply chosen in accordance with recommended published values. On the basis of this kind of type of examination for each spectral interval and absorber this aspect of the radiation scheme of DWD was considered to be fully validated. However, as will be demonstrated later, circumstances may exist, where our judgement based on the off-line validation may be wrong.

The complexity of a radiative transfer scheme implies that it is almost impossible to have a close look at all details. An overall impression of the validity of the approach is therefore essential. In the absence of appropriate measurements of radiative fluxes and heating rates this is typically done by comparison of results

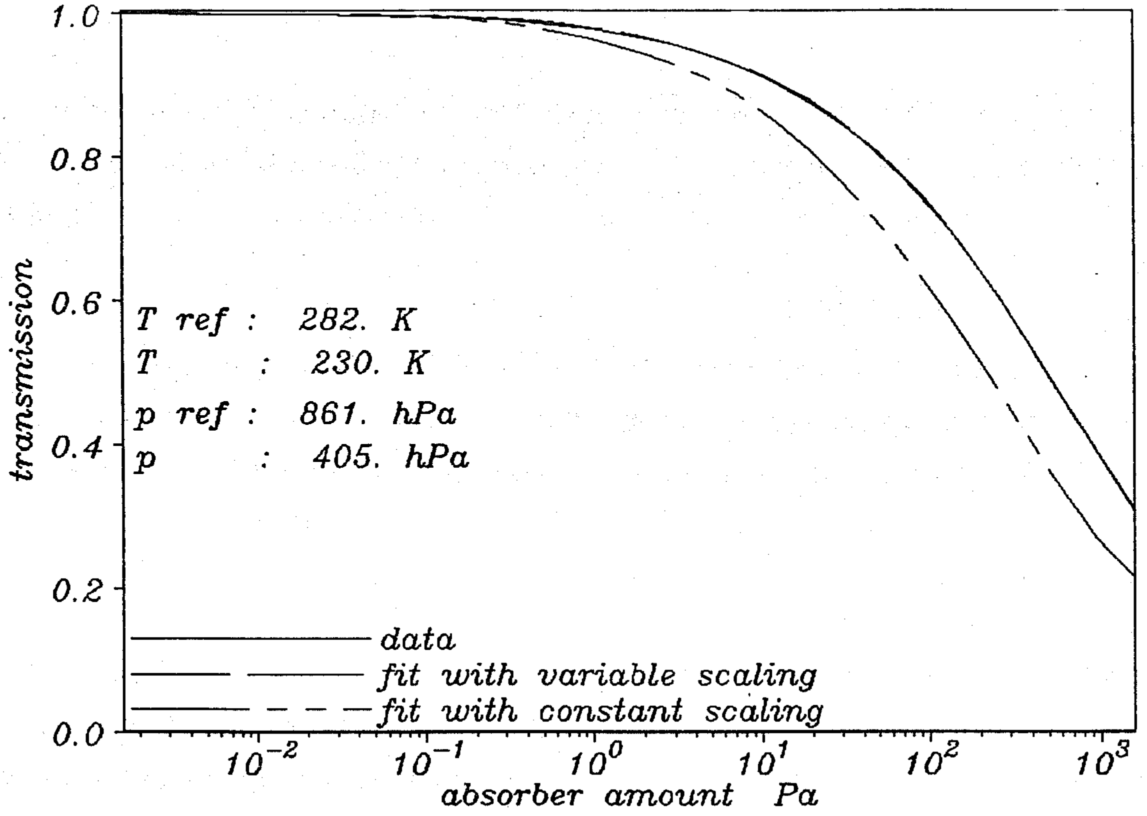

Fig.3: Comparison of the band model transmission function for H_2O in the interval 12.5-20 μm with fitted transmission functions using either constant temperature and pressure scaling or absorption coefficient dependent scaling for deviations from the reference conditions

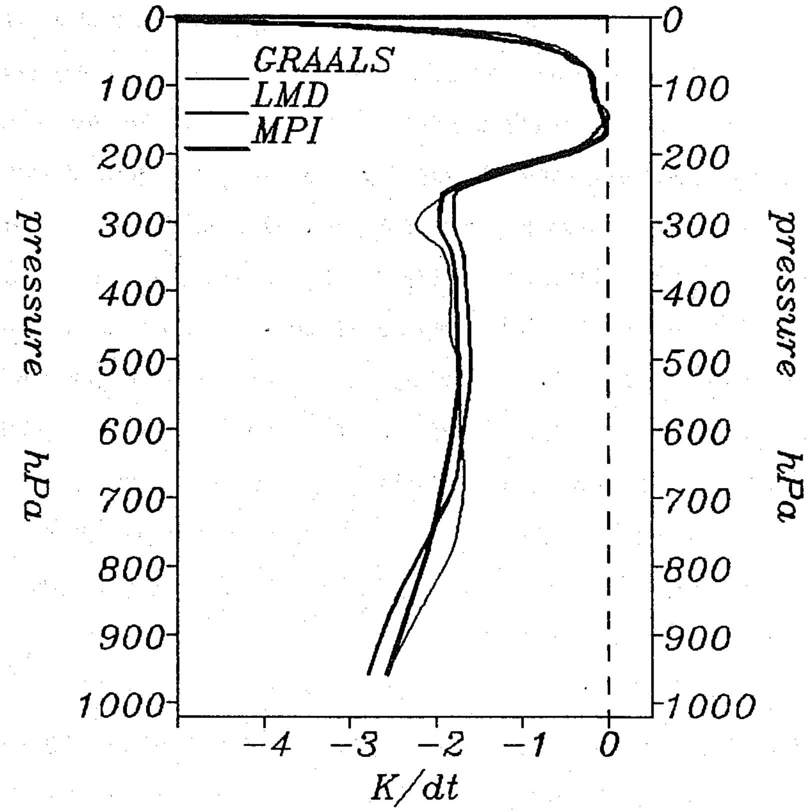

Fig.4: Thermal heating rates in a clear-sky midlatitude summer atmosphere (from RG92). Comparison between line-by-line models (LMD, MPI) and the DWD radiation scheme (GRAALS)

from the highly parametrized scheme with sophisticated reference calculations. Reference calculations with line-by-line models are generally available for a number of atmospheric conditions in the thermal part of the spectrum. Fig.4 illustrates a comparison of heating rates in the midlatitude summer atmosphere. The DWD scheme, denoted by GRAALS is as close to either of the line-by-line results as the two line-by-line results are to each other. This obviously indicates that the uncertainties in the underlying spectroscopic data, which affect all schemes, is at least as detrimental to the results as the loss of accuracy caused by the approximations in our model.

For the solar part of the spectrum, no comprehensive line-by-line reference calculations were available. In order to check NWP type radiative transfer schemes, one therefore often resorts to a comparison with so-called narrow band models (NBM), which resolve the spectrum much better than the wide band NWP type scheme, but by far not as well as a line-by-line model. Fig.5, taken from *Morcrette* (1990) illustrates such a comparison. For the solar heating rates at both zenith angles one wide band model (NEW) and the NBM agree quite well. The results of another wide band model (OPE) seem to indicate an overestimation of the solar heating rates in the troposphere. However, this first impression may be misleading. As for the thermal spectral domain, there is a large uncertainty with regard to the true gaseous absorption properties. The range of this uncertainty is demonstrated in Fig.6, which shows the absorption curve for water vapour integrated over the whole solar spectrum according to various sources. The curve underlying the DWD radiation scheme is rather similar to the one used formerly in the scheme denoted by OPE in Fig.5. Even though this curve indicates the strongest water vapour effect, it is not much different from the one reported by *Lacis and Hansen* (1974). The lowest absorption curve forms the basis both for the NBM and for the WBM, denoted as NEW in Fig.5, thus indicating a considerably lower potential for solar heating in the troposphere. There is no clear indication which of the curves corresponds to the truth, but it has been noted by *Kratz and Cess* (1985) that two small, but nevertheless important absorption bands were omitted in the calculations of *Chou and Arking* (1981), explaining to some extent, why their solar water vapour absorption curve is rather low. Kratz and Cess estimate, that the omitted bands contribute approximately 0.2 K/day to the tropospheric heating. This demonstrates clearly that a lack of knowledge about the true value of solar absorption curve translates directly into a lack of knowledge about the true solar heating rates.

Based on the examples shown, one may draw a preliminary conclusion with regard to the value of off-line validation studies. They are a useful and important tool to establish some basic confidence in a parametrization scheme, but one should not overrate their information content with regard to the true capabilities and deficiencies of the scheme. As will be demonstrated later, the most important shortcoming of this kind of evaluation is the lack of information about the importance of a particular deficiency (or strength) of the parametrization scheme for the evolution of the model forecast.

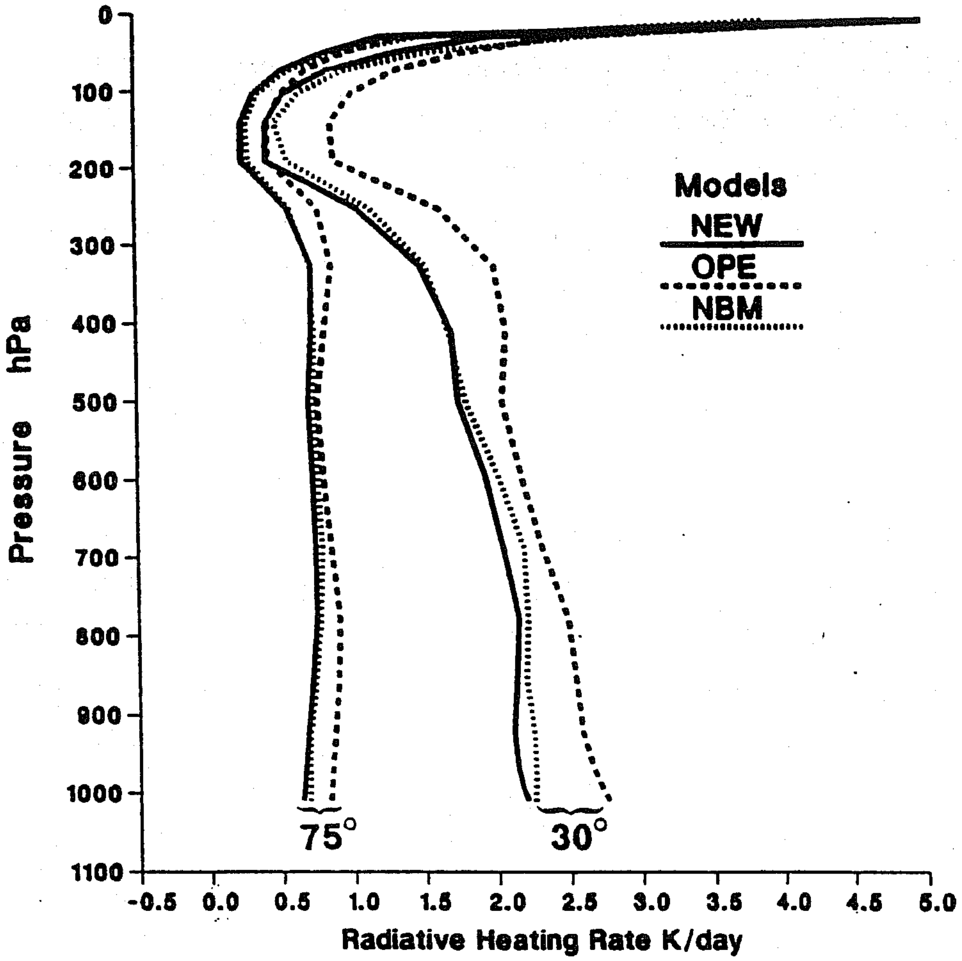

Fig.5: Solar heating rates in a clear-sky midlatitude summer atmosphere for two zenith angles (from Morcrette, 1990). Comparison between different wide band models (OPE, NEW) and a narrow band model (NBM)

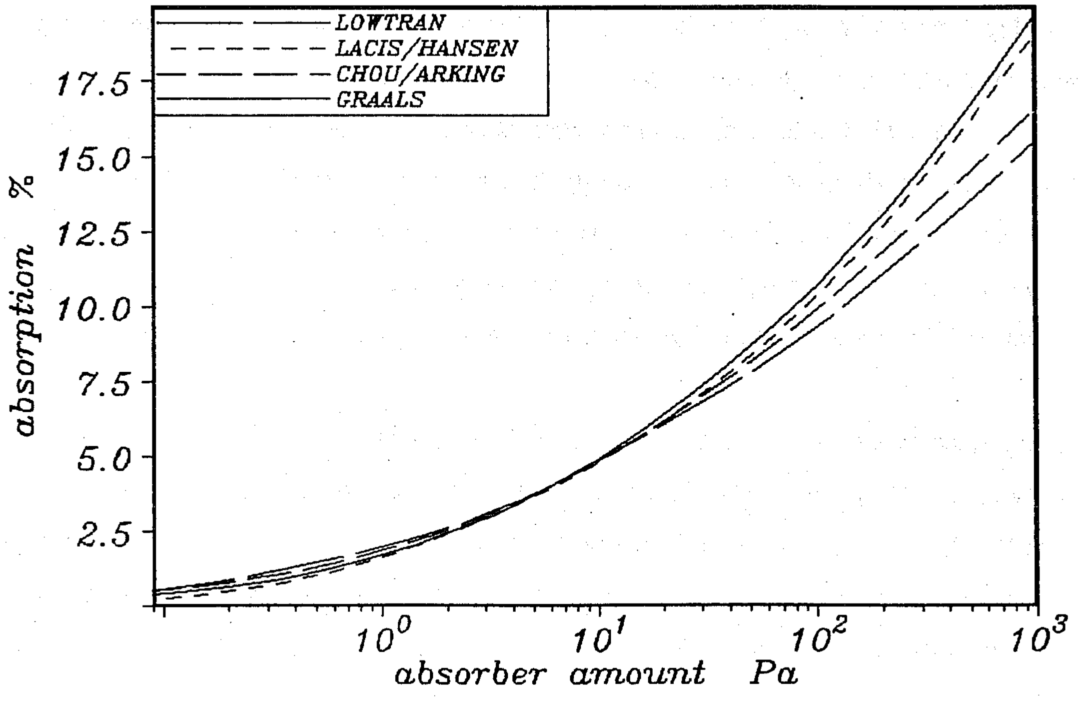

Fig.6: Comparison of solar absorption functions for water vapour at standard temperature and pressure as used in different radiative transfer schemes

3. ON-LINE VALIDATION OF RADIATION AND CLOUDS: CONCEPTS AND RESULTS

3.1 Classical methods

A first impression of the impact of any new parametrization scheme, when it is incorporated in an atmospheric model, may be gained from a study of the energy and hydrological budget. Ideally, one would like to look at annual and global mean values, since in those space-time domains a balanced budget should be simulated both at the top of the atmosphere and at the surface of the earth. Unfortunately, annual integrations of a complete forecast model, or alternatively a sequence of several hundred short range forecast, are far too expensive to be considered for testing purposes. However, an 'a posteriori' evaluation, i.e. the comparison of the model output for a year before and a year after the operational implementation of important model changes is quite common. A whole set of important changes was introduced in the ECMWF operational forecast model in May 1989. The so-called Version 2 of the radiation scheme was replaced (cf. *Morcrette*, 1990) and a mass flux scheme was introduced for the parametrization of convective processes (cf. *Tiedtke*, 1989). In addition to these complete replacements of existing parametrization schemes, the parametrization of gravity wave drag was modified. The impact of these changes on the annually averaged global mean energy budget is discussed in detail by *Arpe* (1991). As an example, Fig.7 taken from the paper by Arpe illustrates the components of the budget for the first 24h of the operational integrations in the year before and after the change of the parametrization schemes. Apart from the identical solar influx at the TOA, all components of the budget are affected by the changes. The differences in the absorption of solar radiation by the atmosphere and the surface are probably to a large extent a consequence of differences in the water vapour absorption functions between the two radiation schemes. This rather direct impact of the model change on the solar surface flux translates into larger fluxes of sensible and latent heat. Since the sea surface temperature is kept constant in the ECMWF model, the forcing of the surface by the larger solar surface flux influences only the land regions directly. The increase in the globally averaged surface heat flux results therefore mainly from the contribution of land surfaces. The fact that the larger solar surface flux, which leads to larger maxima of the land surface temperatures, has very little impact on the thermal radiative flux at the surface is probably related to the concurrent replacement of the thermal radiative transfer scheme.

In neither of the two years do the simulations obey the balance conditions at the atmospheric boundaries or for the atmosphere itself. However, the large discrepancy in the absorption of solar radiative fluxes causes a shift of the imbalance of the energy budget from the atmosphere to the surface. A common problem for both model versions is the imbalance in the hydrological budget; the release of latent heat in the atmosphere by convective and large scale condensation processes exceeds by far the latent heat flux at the surface. Later in the forecast range, when the interaction between the various model components has progressed further, the various budget components and also the net balance are somewhat different, but the main differences between the two years are similar (cf. *Arpe*, 1991).

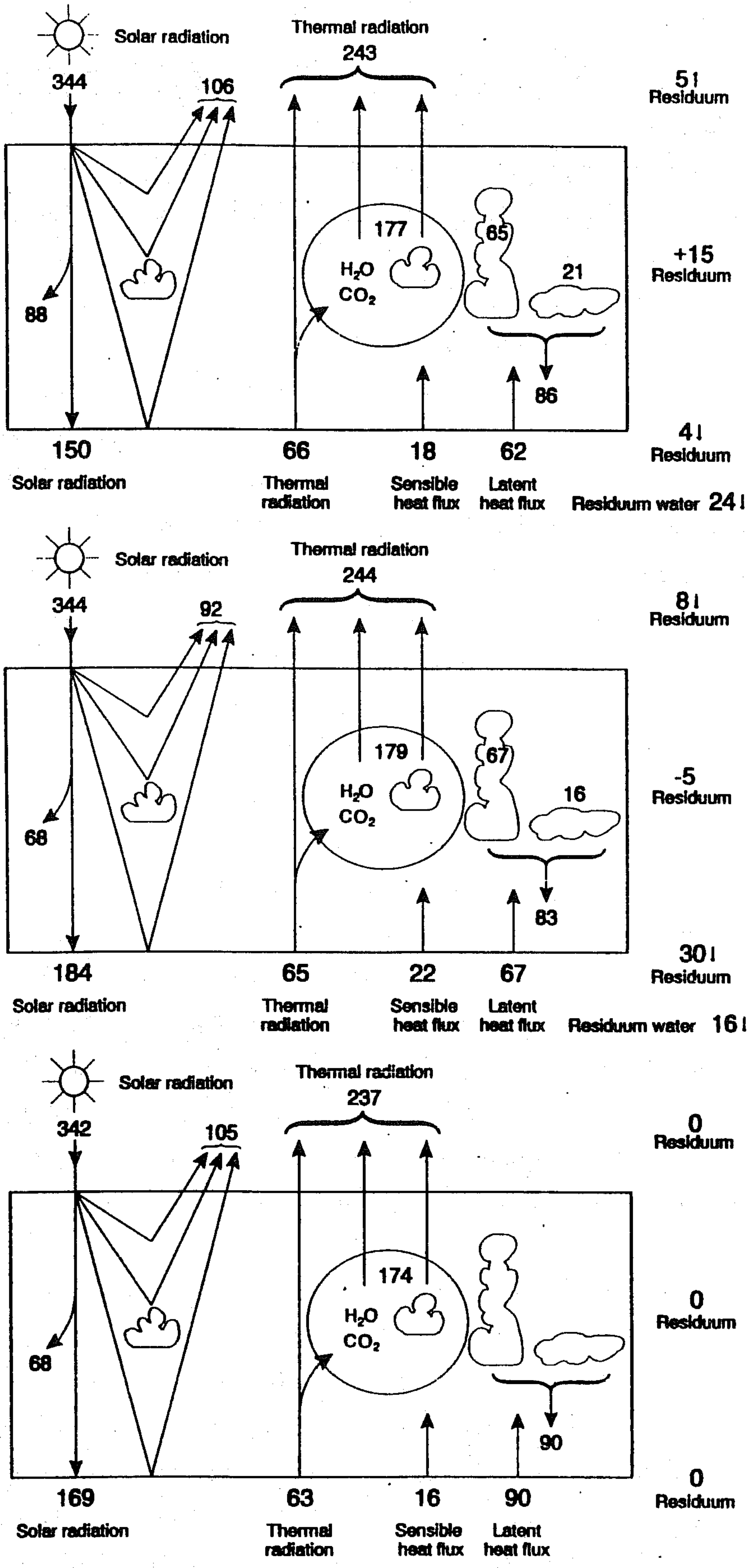

Fig.7: Annual mean energy budget for Day 1 of the ECMWF operational forecasts for one year before (top) and after (middle) the introduction of important model modifications. The bottom panel illustrates a climatological estimate by Ramanathan et al. (1989). From Arpe (1991).

The investigation of the model behaviour with regard to the simulation of energy and water balance forms part of a validation exercise, but without a true reference value for the individual budget components, it is almost impossible to pin-point a specific cause for the violation of the budget balance conditions. For this reason so-called climate estimates of the individual budget components are often introduced as reference values (cf. Fig.7, bottom panel). A detailed discussion of the comparison of the climatological estimate, which is based on values provided by *Ramanathan et al.* (1989), with the results from the two years of operational forecasting at ECMWF is provided by *Arpe* (1991). The usefulness of such a climate estimate for the purpose of model validation is strongly connected to the question whether the estimate is a close representation of the atmospheric truth. A close inspection of the original paper by *Ramanathan et al.* (1989) reveals, that only the TOA radiative budget components are based on observations. According to *Ramanathan et al.* (1989) all other components are derived from (unspecified) model calculations. For this reason, it would be rather naive to consider the values from this particular 'climate estimate' as a reliable reference for the validation of any other model. Consequently, one has to address the question, are there any other, more reliable, estimates of those components of the global mean energy and hydrological budget that can not be measured from space.

Starting with a paper by *Dines* (1917) a considerable number of estimates of the earth-atmosphere energy budget components were published. A selection of published estimates from the last few decades is presented in Fig.8a-h. The results are not directly comparable, since some authors provide only hemispheric averages. However, despite this inconsistency, the spread of values is still disturbingly large. The magnitude of the differences varies from component to component. With regard to the large discrepancies in the atmospheric solar absorption found for the two years of ECMWF model integrations, it is of particular interest that both results are well within the range of the climate estimates for this particular component. Unfortunately, even this fact may not be considered as evidence of model validity. There is actually very little justification at all to use any of these 'climate estimates' as a reference in model validation studies. Essentially all estimates are based on more or less, but typically less, sophisticated model calculations. To illustrate this point, let's look at the approach employed by *Hoyt* (1976), who is often quoted as a source of reference values. Based on zonally averaged values of the radiative input quantities (temperature, moisture, cloud cover, etc.) he performed solar and thermal radiative transfer calculations with a 'state-of-the-art', but still rather simple parametrization scheme. An equally simple parametrization scheme was then used to distribute the net radiative surface fluxes to fluxes of sensible and latent heat. In order to represent the seasonal variation and also to be able to obtain annual averages the calculations were performed for 4 days distributed through the year. The only advantage of Hoyt's approach over the ECMWF (or any other contemporary operational model) results lies in the use of observed values for some of the relevant input quantities. It would be rather

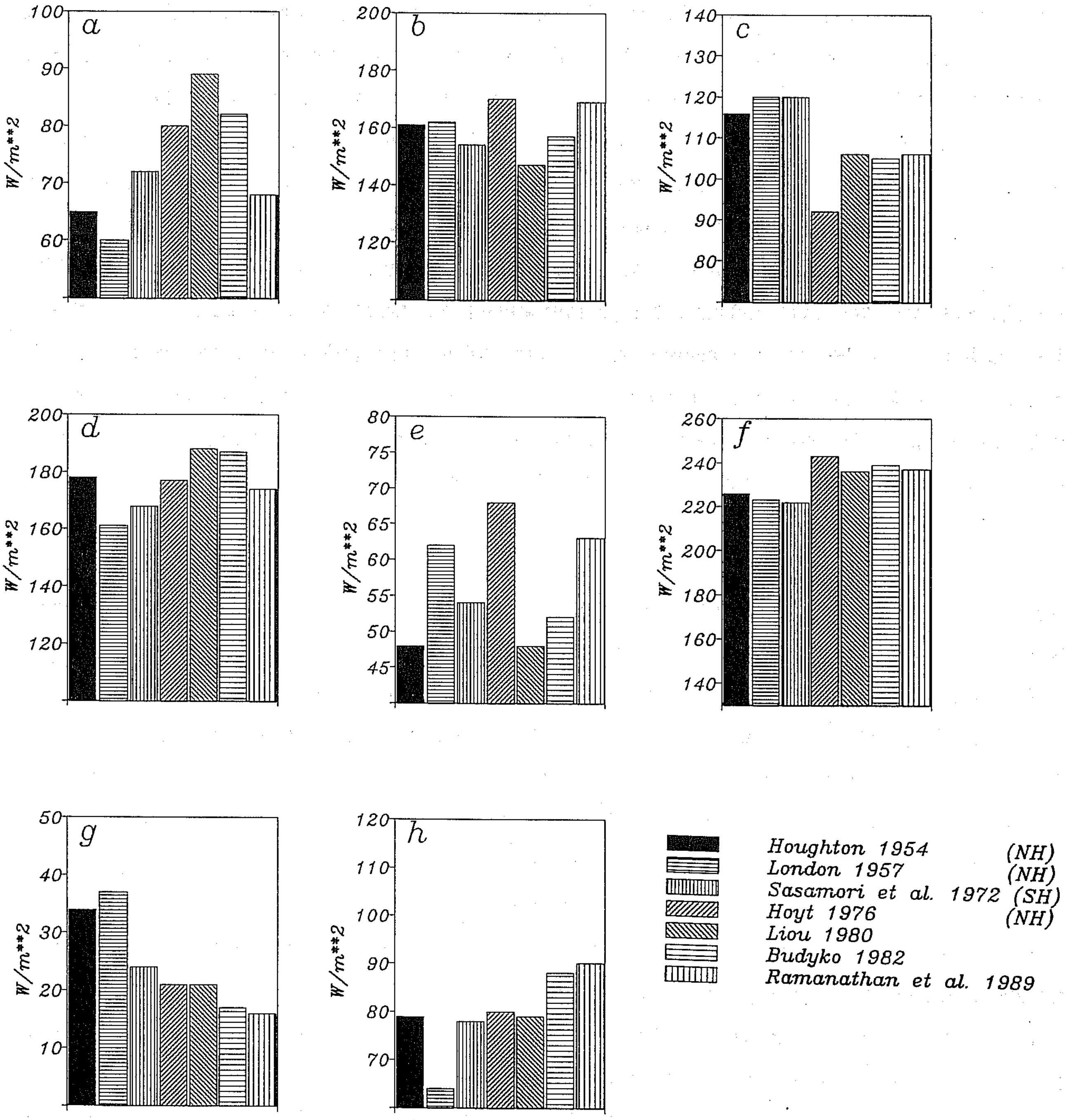

Fig.8: Comparison of several climatological estimates of the energy budget of the earth-atmosphere system.**a**: atmospheric absorption of solar radiation, **b**: net surface flux of solar radiation, **c**: total reflection of solar radiation by the earth-atmosphere system, **d**: net atmospheric emission of thermal radiation, **e**: net atmospheric emission of thermal radiation by the surface, **f**: net emission of thermal radiation by the earth-atmosphere system, **g**: surface sensible heat flux, **h**: surface latent heat flux

naive to assume that this aspect is distinctive enough to justify the use of Hoyt's values as reference for the model results.

The spread between the various 'climate estimates' would probably be even larger, if the constraint of the energy balance at the atmospheric boundaries was not built into the methods used for the derivation of the budget components. A reduction of the potential spread in the results is also attributable to a certain amount of incest, i.e. one author basing his results to some extent on previously published data by another investigator. E.g. *Liou* (1980) performs only an independent calculation for the radiative transfer part and uses the Bowen ratio of *Sasamori et al.* (1972) to share the net radiative gain of the surface between the sensible and latent heat flux.

There has been considerable progress both in modelling of atmospheric processes and in the observational networks since the publication of most of the global energy budget estimates. One could therefore come to the conclusion that an optimum estimate of the budget components could be obtained from the results of the most up to date general circulation and/or NWP models. However, a model intercomparison exercise described in detail in papers by *Cess et al.* (1989) and *Randall et al.* (1992) illustrates dramatically that there is virtually no agreement between various models even with regard to globally averaged properties of the atmospheric state and evolution. For an ensemble of 19 models, subjected to the same initial conditions for a perpetual July simulation with specified sea surface temperature, a wide range of values for the components of the surface energy budget is documented in Table 2 of *Randall et al.* (1992). Fig.9a-e illustrate both the individual components and also the net budget at the surface obtained in the integrations with the various models. Not only is there a large spread in the individual components, also the models do not agree about the magnitude of the net global energy gain or loss at the surface. There is not even agreement with regard to the sign of the net surface budget. Surface cooling effects of up to 40 W/m^2 are in strong contrast to a surface warming by up to 10 W/m^2. Such extreme discrepancies are extremely worrying with regard to our ability to predict the atmospheric evolution and it is essential to understand the reasons for the disagreement. An elimination of the more complex aspects of the parametrized processes is one way to trace such discrepancies to their sources. For this purpose *Randall et al.* (1992) compared also the results of the various models for the calculation of radiative fluxes in clear sky conditions, so that the complexity of the interaction between clouds and radiative transfer was eliminated. Fig.10 demonstrates, that even for such basic quantities as the zonally averaged clear-sky thermal radiative fluxes the agreement between the various model is extremely poor.

From the examples shown, it is evident that, with the exemption of satellite observations of the TOA radiative fluxes, no reliable dataset for the validation of globally averaged energy and hydrological budgets exists.

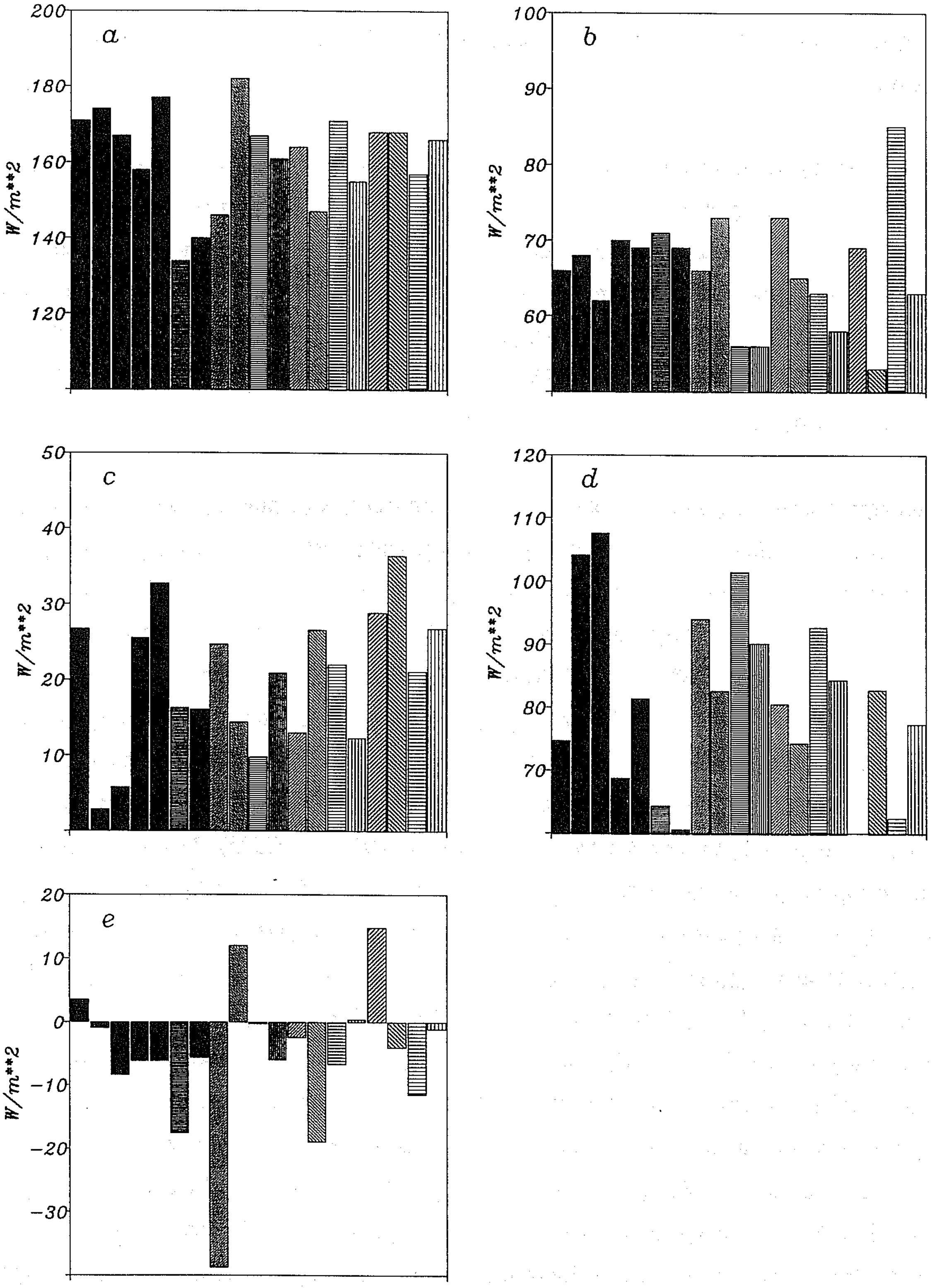

Fig.9: Comparison of model simulations of components of the global surface energy budget after Randall et al. (1992) for perpetual July conditions with a prescribed decrease of 2 K in the sea surface temperature. **a**: net solar surface flux, **b**: net thermal surface flux, **c**: surface sensible heat flux, **d**: surface latent heat flux, **e**: net surface flux

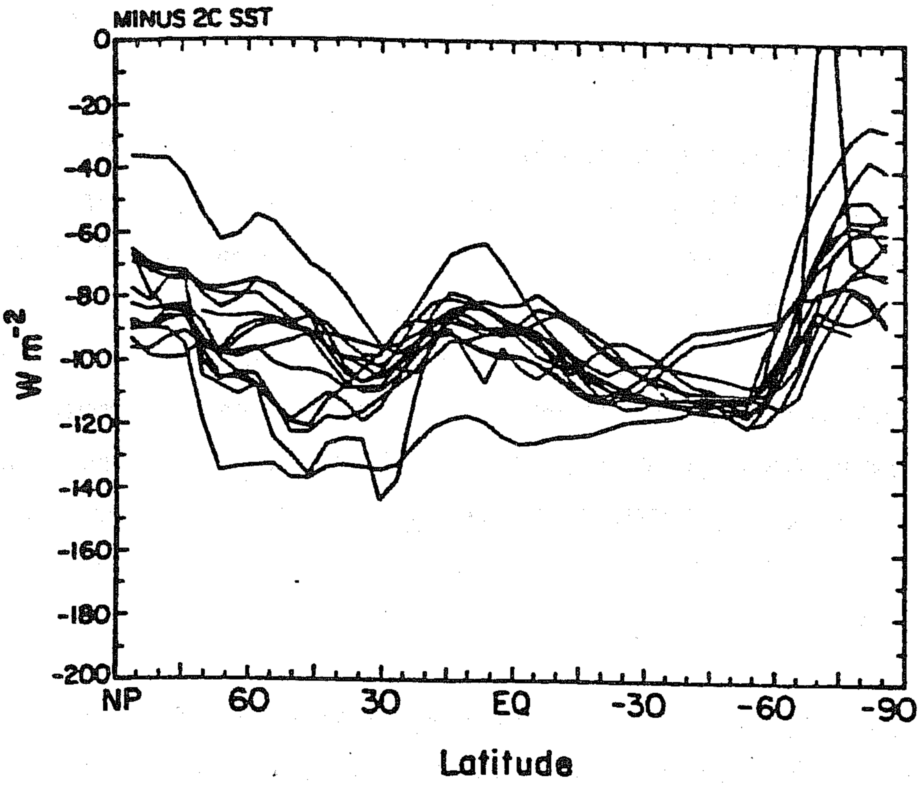

Fig.10: Zonally averaged distribution of clear sky thermal radiative flux at the earth's surface (from Randall et al., 1992, Fig.10). Each line represents one model result.

What is really required are truly observational datasets of these quantities. An attempt to provide such datasets in a form suitable for model validation is undertaken at present as part of the WCP (cf. *Ohmura and Gilgen*, 1991). However, one can infer from the sparsity of suitable observations, that the compilation of reliable global averages remains a formidable, if not impossible task.

Since truly observational datasets are so rare, it is even more important to exploit those that exist to their full potential. The comparison of satellite based estimates of the radiative fluxes at the top of the atmosphere to the corresponding model output fields on a regional scale is a step in this direction. The typical products available from the earth radiation budget experiment (ERBE, cf. *Harrison et al.*, 1990) are maps of monthly averaged radiative fluxes. A map of the OLR for July 1987 (cf. Fig.11a) shows the familiar climatological features. High values of the OLR are found in the warm, dry subtropical subsidence regions, lower values occur towards the poles as a consequence of the increase in cloud cover and decrease in temperature. Clouds, in particular of convective origin and of large vertical extent are responsible for the pronounced innertropical minimum of the OLR. For the purpose of model validation the corresponding model output has to be produced. At this stage one has the choice to select for comparison either the results from an ensemble of short range forecasts (e.g. 30 model integrations over one day) or the temporal average over a single 30 day integration of the model. Which one of the two possibilities is chosen depends mainly on the intended application of the model. The ensemble average is mainly of relevance to NWP. The deviations of these results from reality translate directly into an erroneous forcing of the forecast in the early stages which will have a detrimental impact on the subsequent model evolution and forecast quality. Observed deficiencies are more easily related to specific shortcomings of the model, since the complex interaction between various model components is of lesser importance than in long integrations. A comparison based on the temporal average of a long integration is to be preferred in the context of climate simulation studies. Problems in the modelling of the interaction between various physical processes will show up more clearly, but the interpretation of discrepancies between model results and observations becomes extremely difficult.

The typical application of this kind of validation exercise is the study of differences between two model versions and the observations. So using the second approach, we performed 30 day integrations for July 1992 both with the original ECMWF radiation scheme in the DWD global model and also with the DWD radiation scheme. The results are shown in Fig.11b and c. In both model versions the overall structure of the OLR is similar to the ERBE observations. However, there are also marked differences both between the two versions and also between each integration and the ERBE dataset. With the original ECMWF radiation scheme the ITCZ minimum of the OLR is captured very well in the central american region, but it is too pronounced in the african area. The largest model errors occur in the subtropical subsidence regions, where the model exaggerates the maxima considerably. The experiment with the DWD radiation scheme shows a

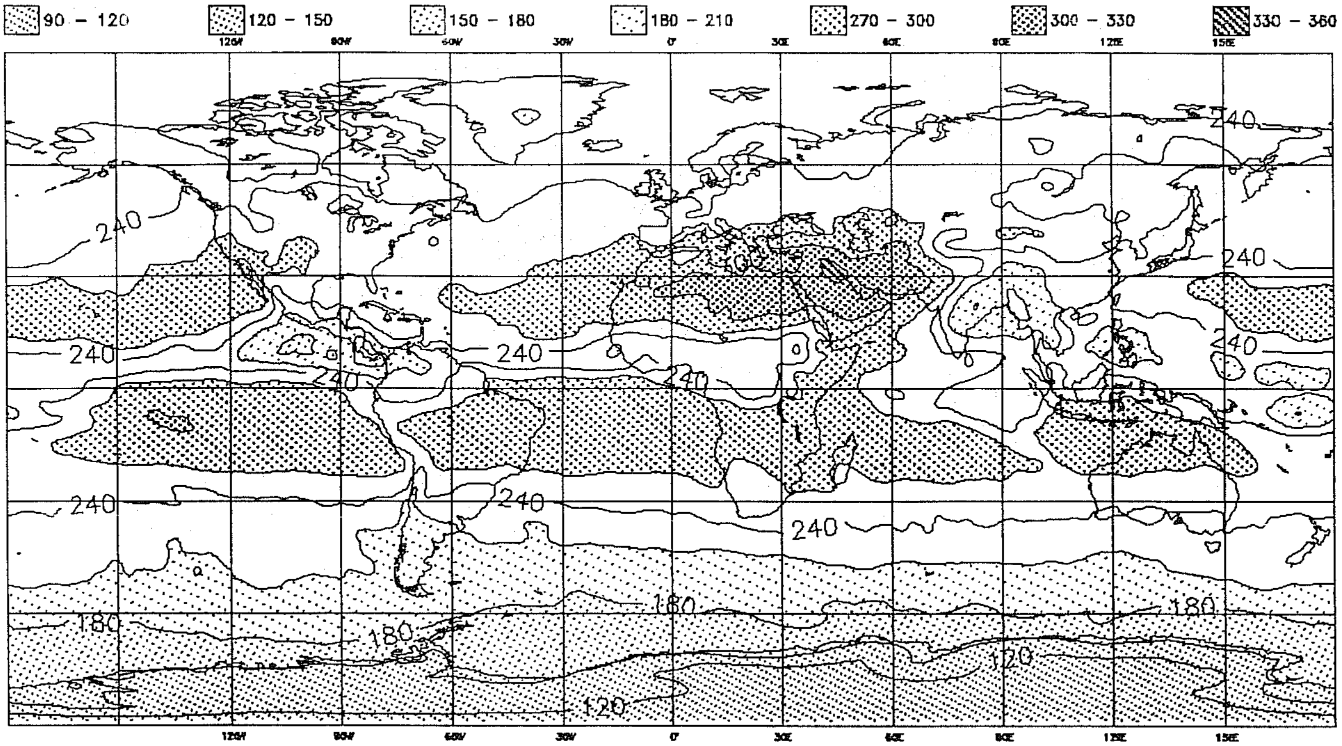

Fig.11a: Monthly mean global distribution of the OLR in W/m^2 as observed for July 1987.

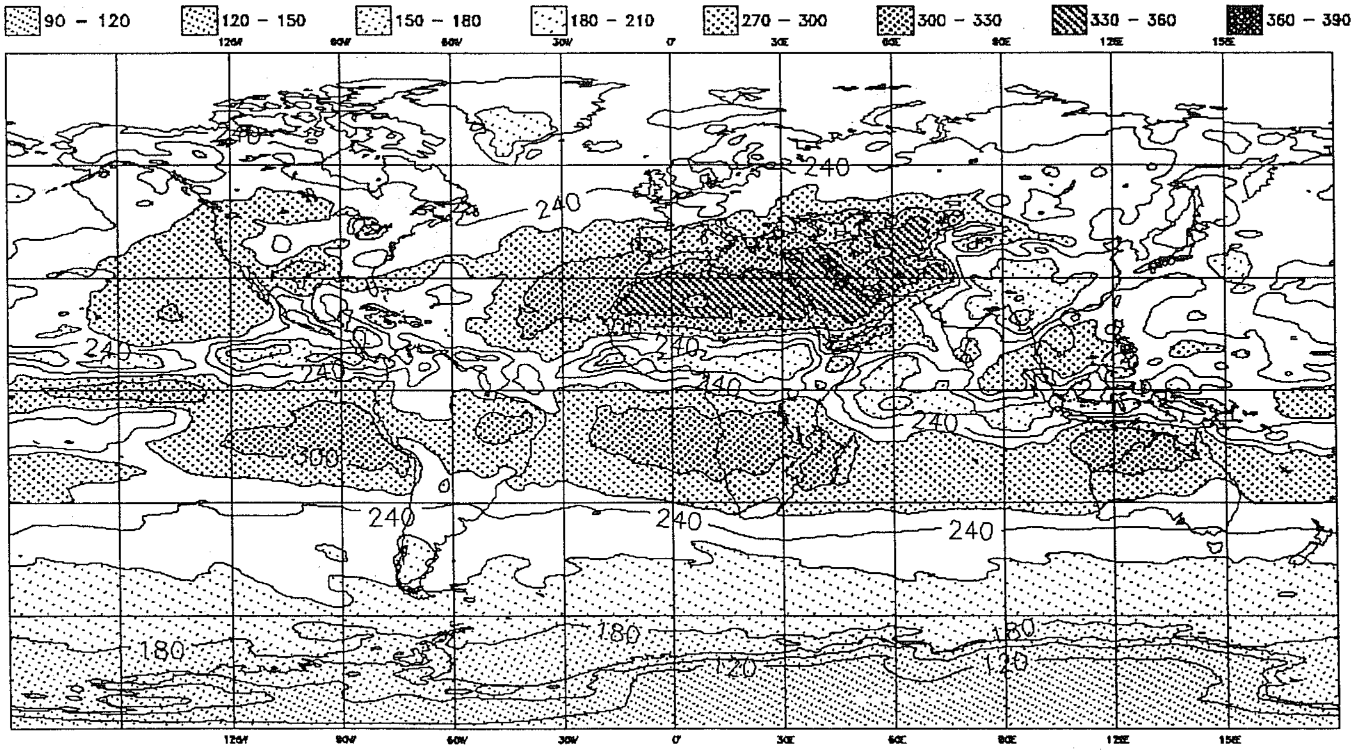

Fig.11b: same as Fig.11a but for a 30 day integration of the global model, using the original ECMWF radiation scheme. Initial date: 1/7/92.

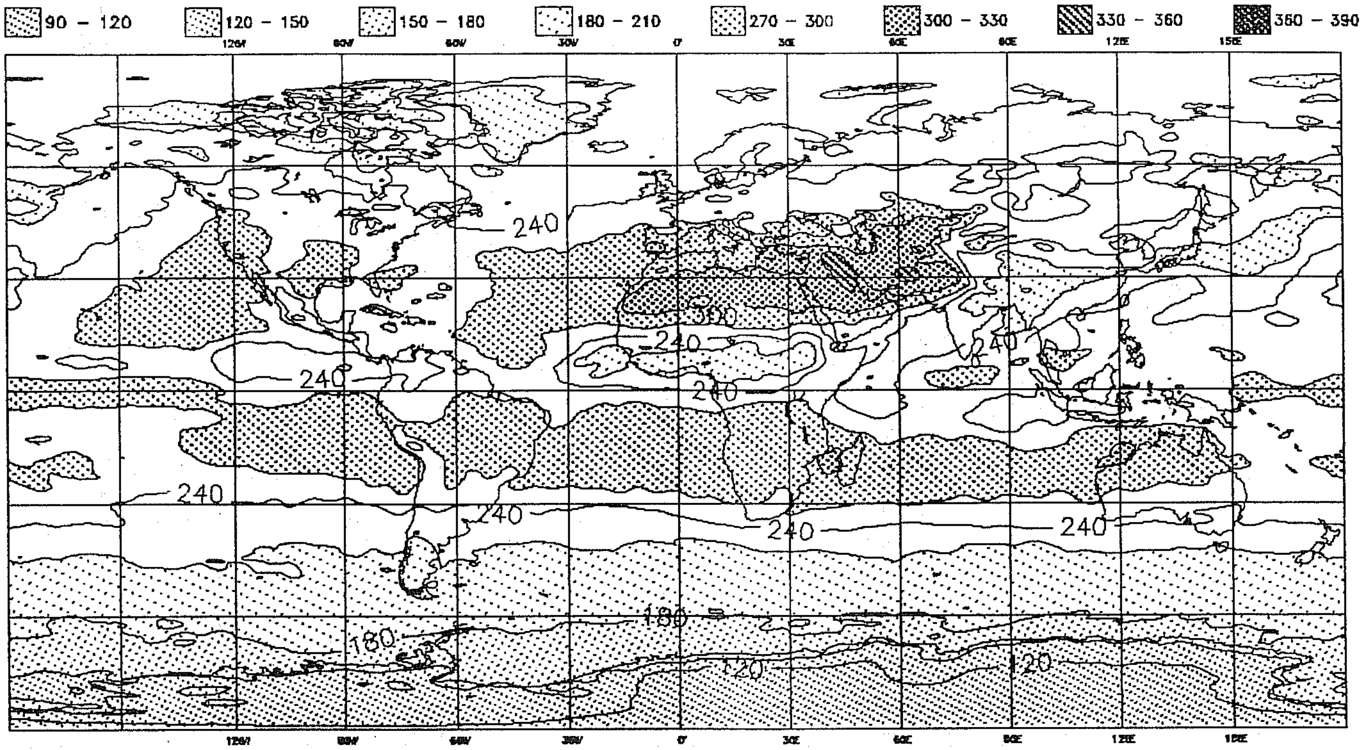

Fig.11c: same as Fig.11b, but using the DWD radiation scheme.

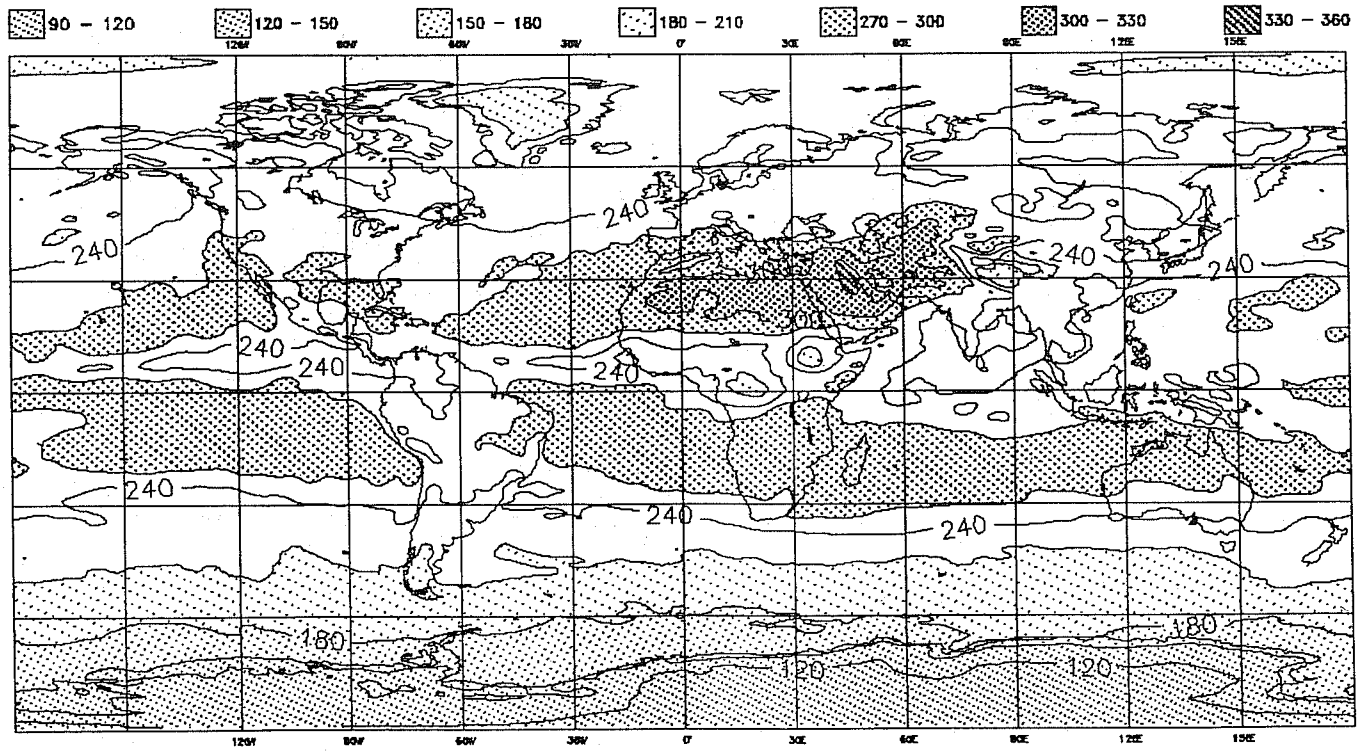

Fig.11d: same as Fig.11c, but for the ensemble of operational one day forecasts of DWD in July 1992.

much better agreement with the observations with regard to the subtropical OLR, but the observed minimum in the central american ITCZ is not predicted as well as with the other scheme. The large differences between the two model versions could, in principle, be related to specific aspects of the individual radiation schemes. However, instead of an extensive discussion of these aspects, let's look at the impact of our choice of temporally averaged results instead of ensemble mean results. Fig.11d illustrates the OLR averaged over all operational integrations with the DWD radiation scheme in July 1992 for day one of the forecasts. Overall, the regional distribution of the OLR is rather similar to the result of the long integration, but there are also areas, where the two approaches yield distinctly different results. Over some regions (e.g. South America) the results from the long integration are actually in much better agreement with the observations than the ensemble mean. The discrepancy between the ensemble mean and the long integration might be attributed to some extent to a spin-up effect, but an inspection of the results of the ensemble mean for day two and three of the forecasts (not shown) does not indicate that such an effect is dominant in the early stages of the forecast. Even if a strong spin-up effect was responsible for some of the discrepancies between the ensemble mean results and the observational dataset, one ought to validate the model fluxes at this stage of the forecast in the context of NWP. The discovery and elimination of model problems that spoil the results in the first few forecast days is bound to improve the forecast quality in the later stages of the integration.

At this point we have not yet addressed the problem of interannual variability. Observational datasets of radiative quantities from satellites are normally only available with a time lag of several years. Since NWP models undergo a continuous development, one typically compares the model results valid for a particular month and year with a satellite dataset for the same month of a different year. Unfortunately, even on a monthly scale, the large scale features of the top of the atmosphere radiative fluxes are subject to a rather strong interannual variability. Even though the basic structures are fairly stable, the year-to-year differences are comparable in magnitude to the differences between model results and observations (*Charlock*, pers.communication). It is therefore indispensable for the detailed validation of radiative aspects to compare observations and model results that are collocated in space and time. Otherwise, any interpretation of discrepancies has to be confined to the coarsest features.

The most likely candidate for the cause of the interannual variability in the OLR is the global cloud distribution. As reported by *Warren et al.* (1986) the interannual variability in the monthly mean values is of the order of 5% in the total cloud cover. To get an idea about the differences between the modelled cloud cover in our integration and the observed cloud cover in the month corresponding to the ERBE dataset, the satellite based ISCCP cloud cover dataset (cf. *Rossow and Schiffer*, 1991) was chosen as reference. As illustrated in Fig.12a, this dataset indicates the expected large cloud amounts over the midlatitude storm tracks and the innertropical convergence regions. Low values over the subtropical subsidence region are also in accordance with expectations. However, the extremely sharp contrast between land and sea and also the surprisingly low values over the polar regions may be a consequence of deficiencies in the algorithm which is required to convert satellite measured radiances in estimates of cloud cover (cf. *Rossow and Schiffer*, 1991; *Stowe et al.*, 1988). Large discrepancies between various satellite based estimates of the global cloud distribution are typically attributed to the sensitivity of the retrieval algorithms to the choice of free parameters (e.g. IR threshold values). However, the existence of this sensitivity with regard to tuning constants implies also a large uncertainty for the final product. This uncertainty is reflected in the statement of Rossow and Schiffer, that the ISCCP products are of experimental character. As evidence for the validity of the ISCCP cloud cover they refer to the overall agreement with the surface based climatology of *Warren et al.* (1986, 1988). However, one should bear in mind that according to Warren et al., the surface based climatology provides the quantity sky cover, i.e. the portion of the celestial hemisphere covered by clouds as seen from a point on the surface. In contrast to this, the satellite viewing position and angle imply that the ISCCP product is closer to the so-called earth-cover, i.e. the vertical projection of the clouds on to the surface of the earth. This quantity is systematically, and depending on cloud type sometimes substantially, smaller than the sky cover. Bearing this in mind the fact that the cloud cover in the model (cf. Fig.12b), which has to be interpreted as earth cover, is substantially smaller than either the ISCCP product or the surface based climatological values, is disconcerting but not alarming. A retuning of the model cloud cover parametrization on the basis of this rather uncertain dataset would obviously be a bit premature, in particular with regard to the fact that the radiative fluxes at the top of the model, are already in reasonable agreement with the observations.

An attempt to further exploit satellite datasets for the purpose of model validation was presented at the International Radiation Symposium 1992 by *Campana et al.* (1992) Through a comparison of modelled solar surface fluxes with values obtained by applying a radiative transfer model to input variables (e.g. cloud cover, optical depth) obtained from the ISCCP dataset they tried to bypass the problem that no truly observational global dataset exists for the validation of radiative fluxes at the earth's surface. However, one could argue that this approach is of a rather limited value for the purpose of model validation. The discrepancies between the NMC modelled cloud cover and the corresponding ISCCP values were at least as large as those illustrated for the case presented in Fig.12. The extremely high correlation between the differences in fluxes and those in cloud cover, which was documented in this study, has to be expected and is simply a reflection of the fact that clouds are the dominant modulator of solar radiative processes. Furthermore, even in areas where both NWP model and ISCCP indicated cloud-free conditions, differences in the solar surface flux may not necessarily be related to deficiencies in the radiation scheme of the NWP model. Since a complete radiative

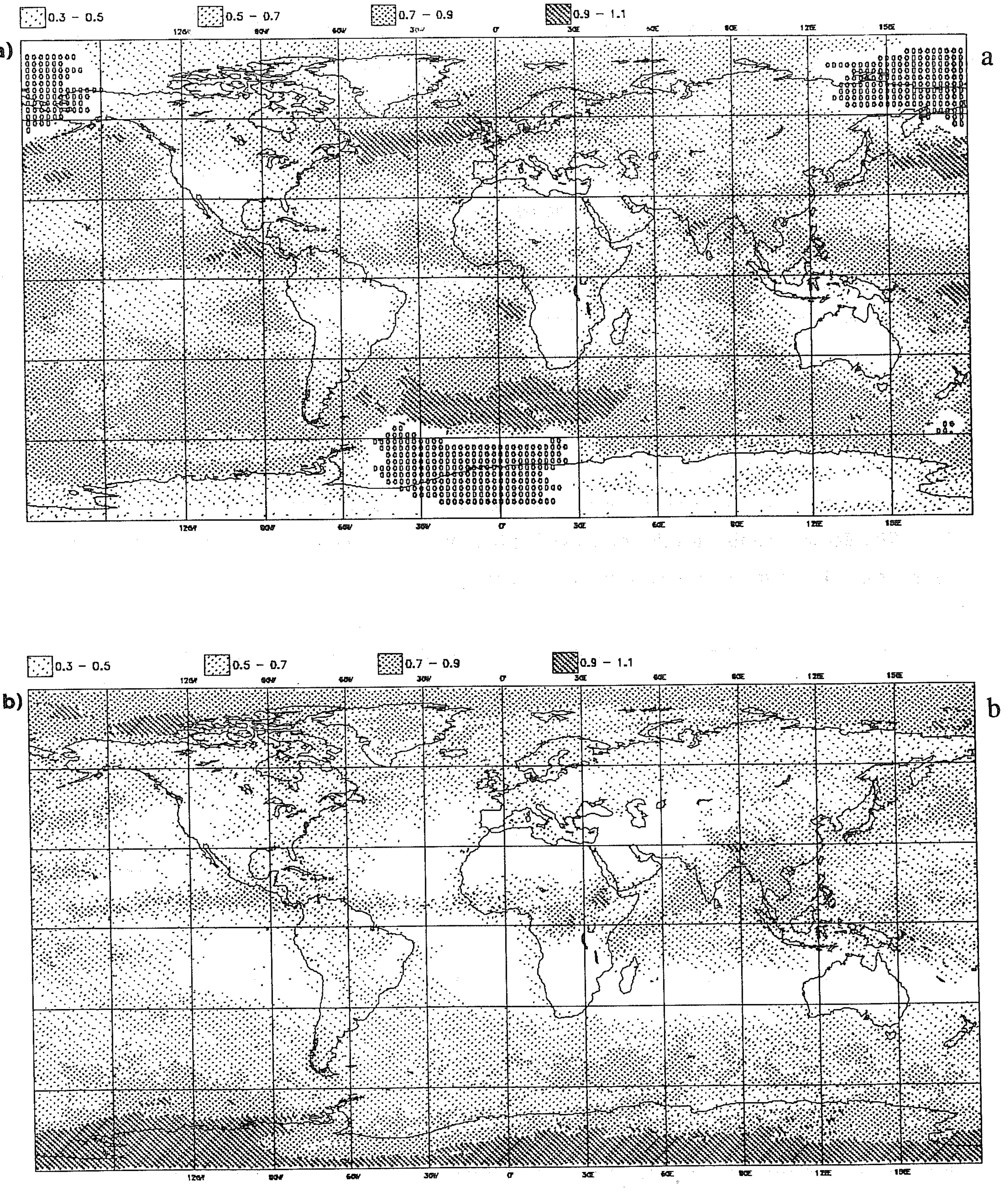

Fig. 12: Monthly mean global distribution of total cloud cover. **a**: ISCCP estimate for July 1987, **b**: results of the 30 day integration with the DWD radiation scheme for July 1992.

transfer calculation is also necessary to convert the ISCCP input to a surface radiative flux (cf. *Pinker and Laszlo*, 1992), the cause of any discrepancy could just as well be a deficiency in this particular algorithm.

The complexity of the interaction between the various components of the forecast constitutes a major handicap for the interpretation of temporally averaged model results. As shown previously, this handicap is aggravated by the fact that useful reference datasets are rare and not always of the desired quality. One alternative to the consideration of temporally averaged quantities is the examination of the evolution of the model state in the course of the forecast period. As a first example, Fig.13 illustrates the temporal behaviour of the components of the globally averaged energy budget in a long integration. The upper panel refers to a 30 day integration for April 1991 with the version of the DWD global model using the original ECMWF radiation scheme, the lower panel represents the corresponding experiment with the DWD radiation scheme. The tendency of the ECMWF radiation scheme (cf. *Morcrette*, 1990) to produce rather high values of the solar surface flux is clearly evident in this illustration. The reduction of the solar surface flux caused by the implementation of the DWD radiation scheme is reflected in a change of the fluxes of sensible and latent heat. The almost immediate reaction of the surface heat fluxes to the change in the solar forcing indicates the close coupling between these components of the energy cycle.

The strong interaction between the surface fluxes is also responsible for the fact that all components indicate a pronounced diurnal cycle. The existence of such a diurnal cycle in globally averaged model fluxes is caused by zonal asymmetries in surface and atmospheric properties in conjunction with the diurnal cycle of the solar angle. The distribution of land and sea and zonal asymmetries in cloud cover are of particular importance, but other, less obvious factors like the surface wetness are also relevant. The relevance of the surface wetness explains why the maximum value of the sensible heat flux coincides with a small relative minimum in the latent heat flux. At this time of the day, the Sahara desert, where only very little surface moisture is available for evaporation, forms a large part of the land mass exposed to a strong solar insolation. In the NWP model only land surfaces may respond directly to the change in the solar forcing, since the SST is kept constant during the integration. For this reason the minima in the sensible heat flux, which are associated with the times when almost exclusively sea points are exposed to the solar insolation, are insensitive to the choice of the radiative transfer scheme.

In itself the comparison of the evolution of the budget components is only an illustration of sensitivity. However, there is often a strong link between those quantities illustrated in Fig.13 and other model products, that may be validated against observations. One such product, which happens to be also of extreme importance for the success of the forecast from the stand-point of the user, is the amount and frequency of predicted precipitation. A comparison of the precipitation amounts predicted in the monthly integrations for

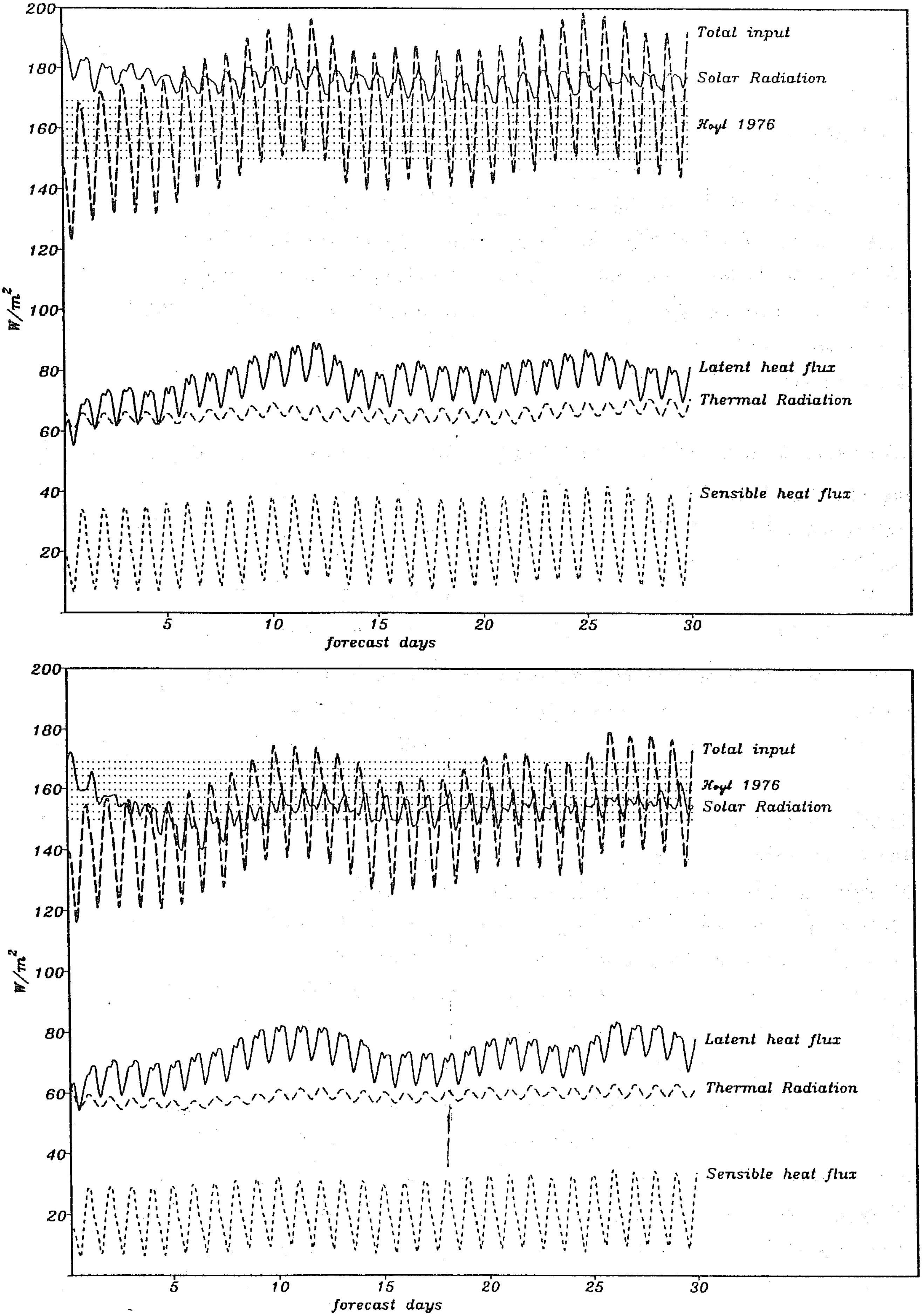

Fig.13: Temporal evolution of globally averaged components of the surface energy budget in extended integrations of the DWD global model. Initial date: 1/4/91. Top: Integration with original ECMWF radiation scheme, bottom: integration with the DWD radiation scheme.

July 1992 over Europe exhibits considerable differences between the two model versions (cf. Fig.14a,b). In comparison to the observational data (cf. Fig.14c) the experiment with the old scheme exaggerates by far the amount of precipitation in the area of southern Germany and the Alps. The precipitation predicted in the experiment with the DWD radiation scheme is generally in better agreement with the observations. The excessive precipitation in the old model version, which was also observed as a very persistent model deficiency in the summer of 1991, when this scheme was used in the operational forecast model, is related to an overestimation of the solar surface flux. As a consequence of the larger surface flux, the daytime near-surface temperatures are overestimated and the convection scheme is triggered to frequently. Thus, both amount and frequency of convective precipitation over land were generally overestimated.

Another aspect of model validation consists of an investigation of the models ability to maintain conservative properties of the atmosphere in the course of the forecast. The globally averaged temperature is not really constant over longer periods of time (cf. *Oort*, 1983). However, even over the period of extended model integrations the variation of this quantity in the real atmosphere is rather small. From the study of the globally averaged energy budget it is obvious that in both versions of the DWD global model a drift in the globally averaged temperature has to be expected. Fig.15a and b illustrate how this drift manifests itself in the course of 30 day integrations in the globally averaged vertical temperature profile. The initial state is characterized by the solid curve and the sequence of dashed curves represents the simulated evolution up to day 30 at intervals of 3 days. The deformation of the tropopause by both model versions in the course of the integration is evident, but particularly dramatic in the integration with the first version of the DWD radiation scheme. The problem is overly accentuated by the use of model levels as vertical coordinate, the same results plotted with a pressure coordinate would provide a stronger indication of the tendency to cool the upper troposphere in the integration with the ECMWF radiation scheme. The deformation of the tropopause structure constitutes a serious flaw of this version of the DWD radiation scheme and instigated a thorough search for the cause of the problem. An examination of zonal averages of the temperature structure and the simulated heating rates of the two model integrations revealed small, but systematic differences in radiative heating rates in the region of the upper troposphere and lower stratosphere. The different radiative forcing at these heights was obviously not balanced by other diabatic or adiabatic processes. For this reason the deformation of the temperature structure in each model version reflected the preferred thermal state of the individual radiation scheme, i.e. the temperature structure where the radiative heating became either extremely small or was balanced by the contribution of other processes. The differences occurred mainly in tropical and subtropical regions, where the determination of the real structure of the temperature field in the stratosphere and upper troposphere is complicated by the lack of reliable observations. The reliance of the assimilation scheme of the model on the model first-guess as a background information permits in such circumstances a strong impact of the model characteristics on the analyzed initial

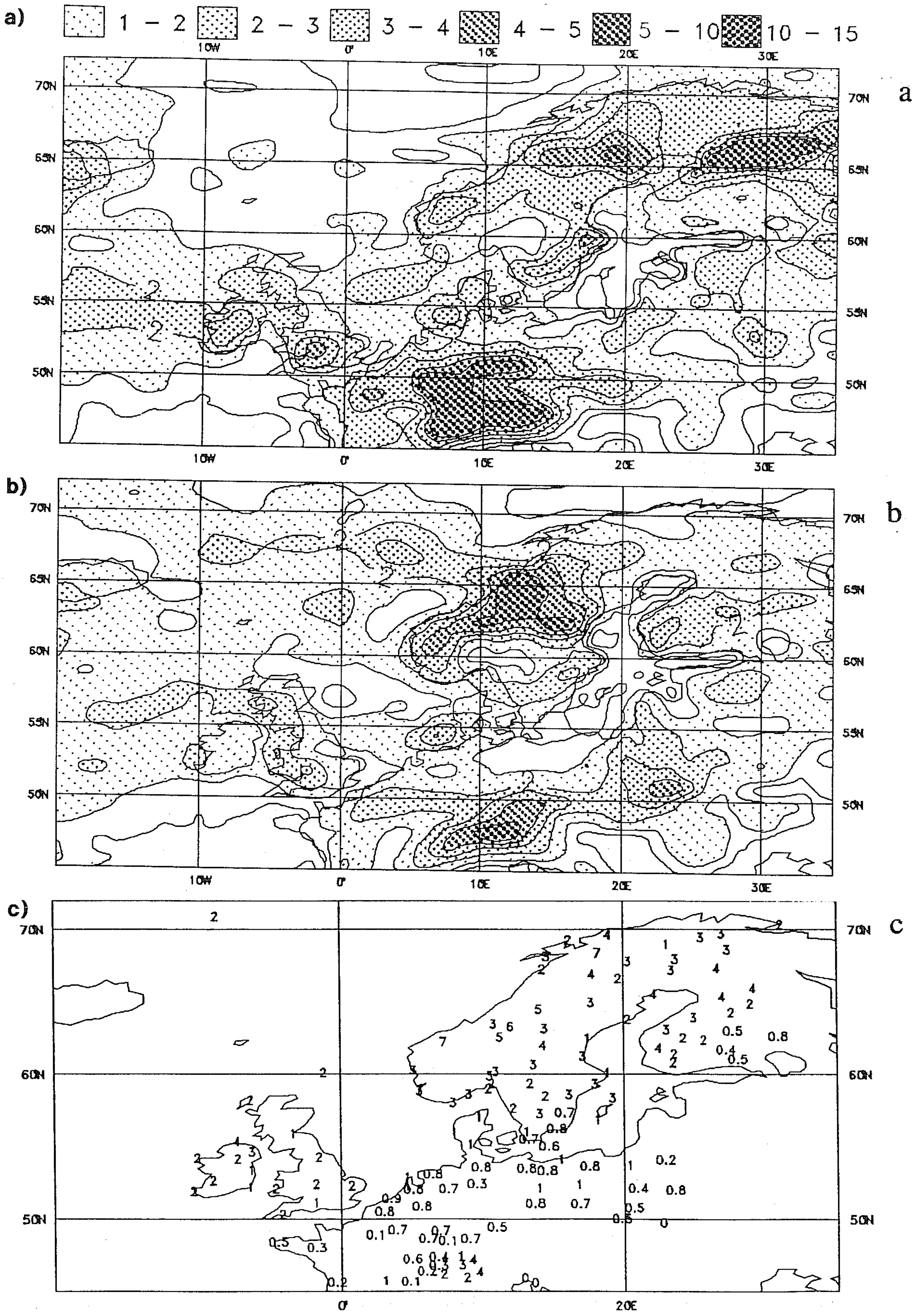

Fig.14: Daily averages of precipitation amounts over parts of Europe for two 30 day model integrations and corresponding observations. a: integration with original ECMWF radiation scheme, b: integration with DWD radiation scheme, c: observations for July 1992.

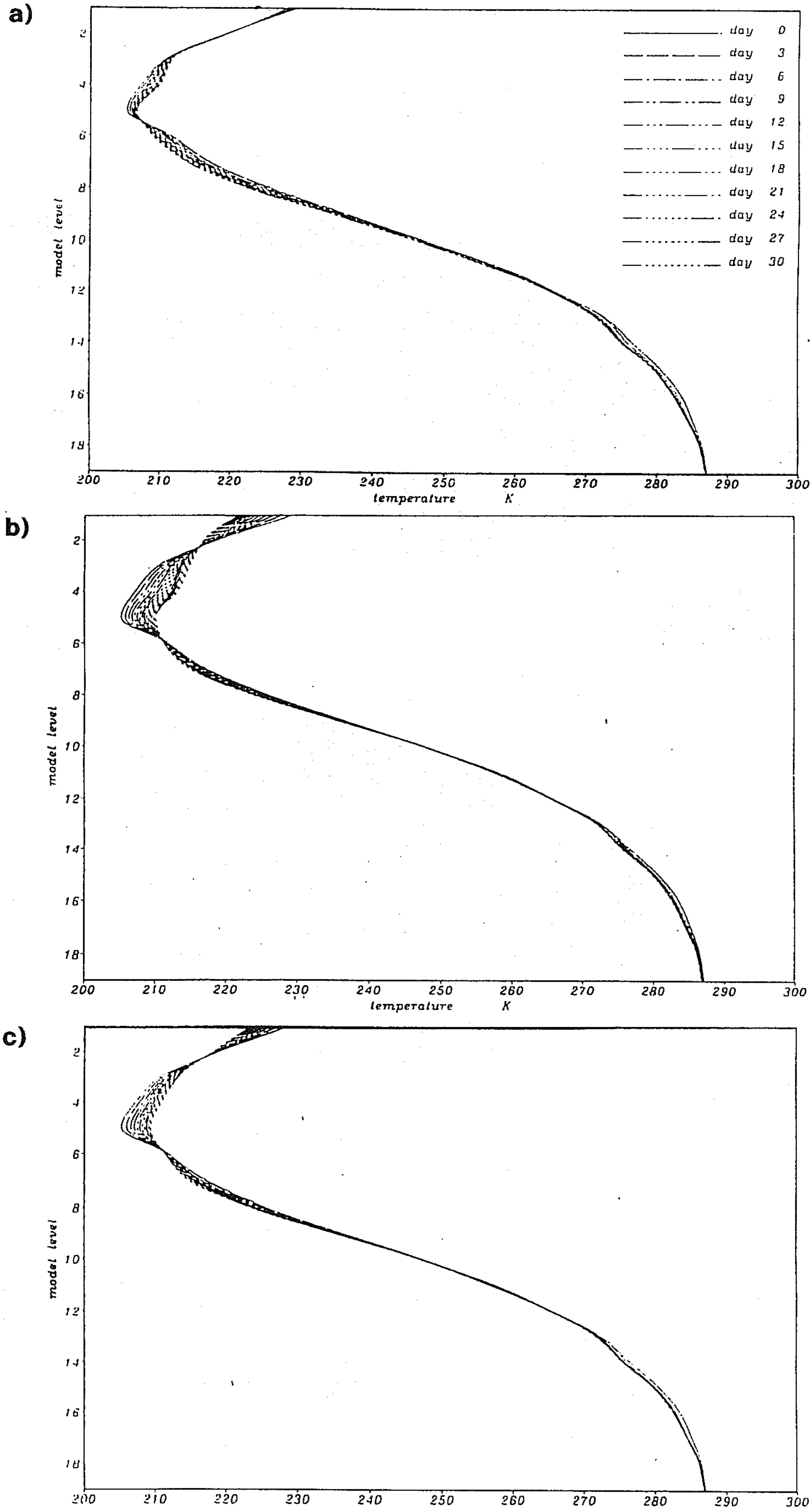

Fig.15: Evolution of the globally averaged vertical temperature profile in extended global model integrations. Initial date: 1/4/92. **a**: Integration with original ECMWF radiation scheme, **b**: integration with first version of DWD radiation scheme, **c**: integration with revised DWD radiation scheme.

state. This fact was clearly illustrated by *Arpe* (1989). A long time series of the area averaged ECMWF analysis of temperature in the tropical tropopause region reveals that modifications of the forecast model often resulted in significant variations of this quantity.

However, since the deformation, observed in our integration, was larger than could be tolerated in the light of the uncertainty about the initial state, a possible explanation and remedy for the differences in radiative heating between the two model versions was sought. A return to the comparison of off-line results with line-by-line models revealed a small but spurious deviation of our thermal radiative heating rates in the relevant region. In absolute terms, this deviation was smaller than the deviations between the different line-by-line models elsewhere in the atmosphere, but it happened to occur at a height where the host NWP model is most sensitive to errors in the simulated heating rates. As shown in Fig.16, the discrepancies could be traced to errors in the treatment of the absorbtion of thermal radiation by CO_2. Using the logarithm of pressure as vertical coordinate, the fact that our results for CO_2-only calculation deviate considerably from the line-by-line results of the LMD scheme (cf. *Scott and Chedin*, 1981) in the region of the tropopause becomes rather obvious. The erroneous heating was caused primarily by our choice of reference pressure and temperature in our fitting algorithm of the carbon dioxide band transmission function. Since the validity of our choice at the time of the off-line calculations was checked mainly by a comparison of original and approximated transmission functions, the true importance of small deviations at this stage for the evolution of the numerical forecast model was underestimated. Instigated by this finding, one ought to revise this kind of fitting algorithm completely. Deviations of the approximated curve from the original are not always an adequate measure for the validity of the approximation. The particular aspect of interest (e.g. temperature evolution in long integrations, radiative surface fluxes for short range forecasts) should be represented in the penalty function of the fitting algorithm. Unfortunately, the co-occurrence of competing objectives and the fact that in general it is rather difficult to foresee which model aspect will be sensitive to a certain detail of a parametrization scheme imply that in most situations one will have to use the standard method. In our particular problem, it was sufficient to move the pressure and temperature reference values from their original midtropospheric values closer to the tropopause region. This measure was sufficient to bring the radiative heating rates in the lower stratosphere of our scheme in much better agreement with the line-by-line results (cf. Fig.17). The small increase of the deviations in the lower troposphere is even smaller in the presence of other absorbing gases (not shown) and is also of little relevance to the model simulation. A long integration with the revised version of the DWD scheme still exhibits a deformation of the temperature structure (cf. Fig.15c), but the magnitude of the deviations, which is considerably smaller than in the integration with the original version, can be accepted, bearing in mind the dependence of the initial state on the model used in the data assimilation scheme.

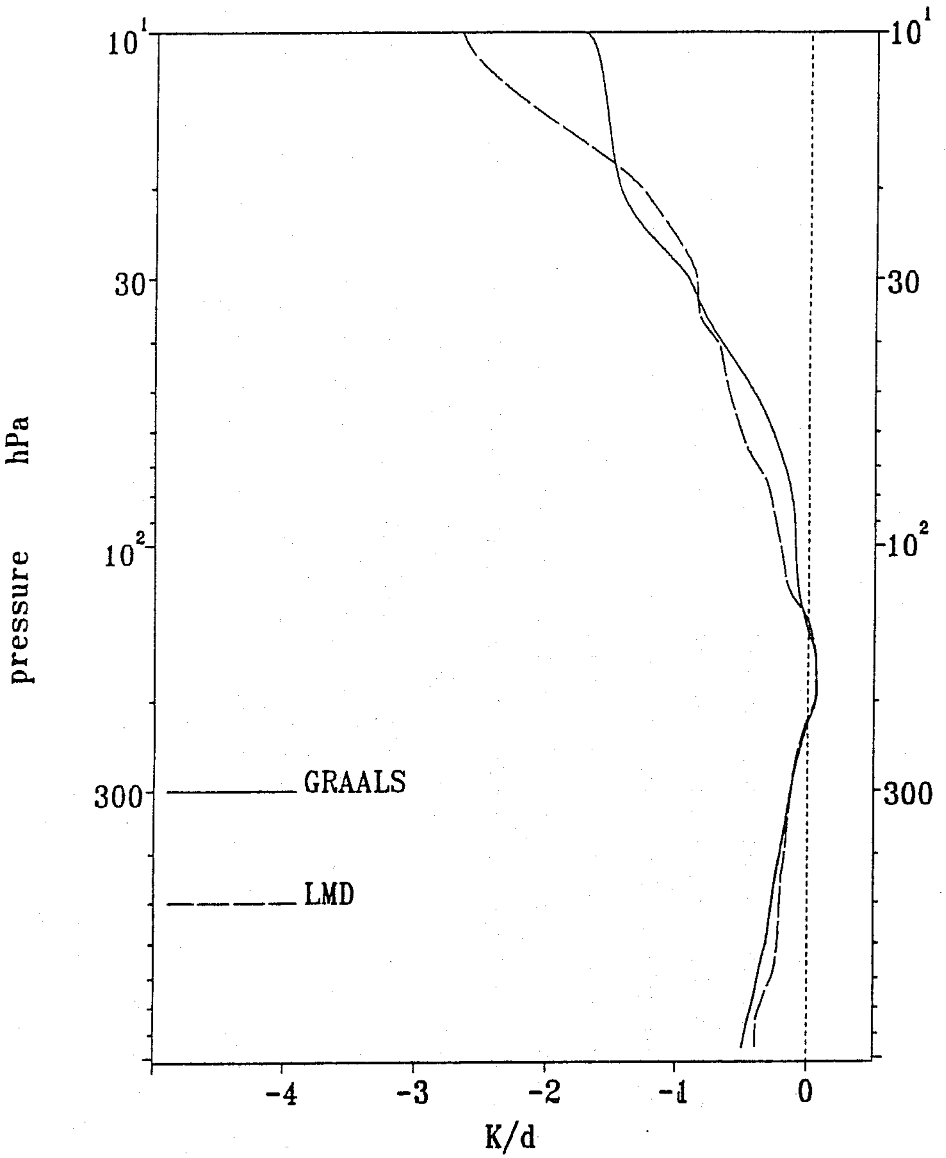

Fig.16: Comparison of thermal radiative heating rates in a clear-sky midlatitude summer atmosphere from line-by-line calculations and the first version of the DWD radiation scheme (GRAALS) CO_2 is the only absorber considered.

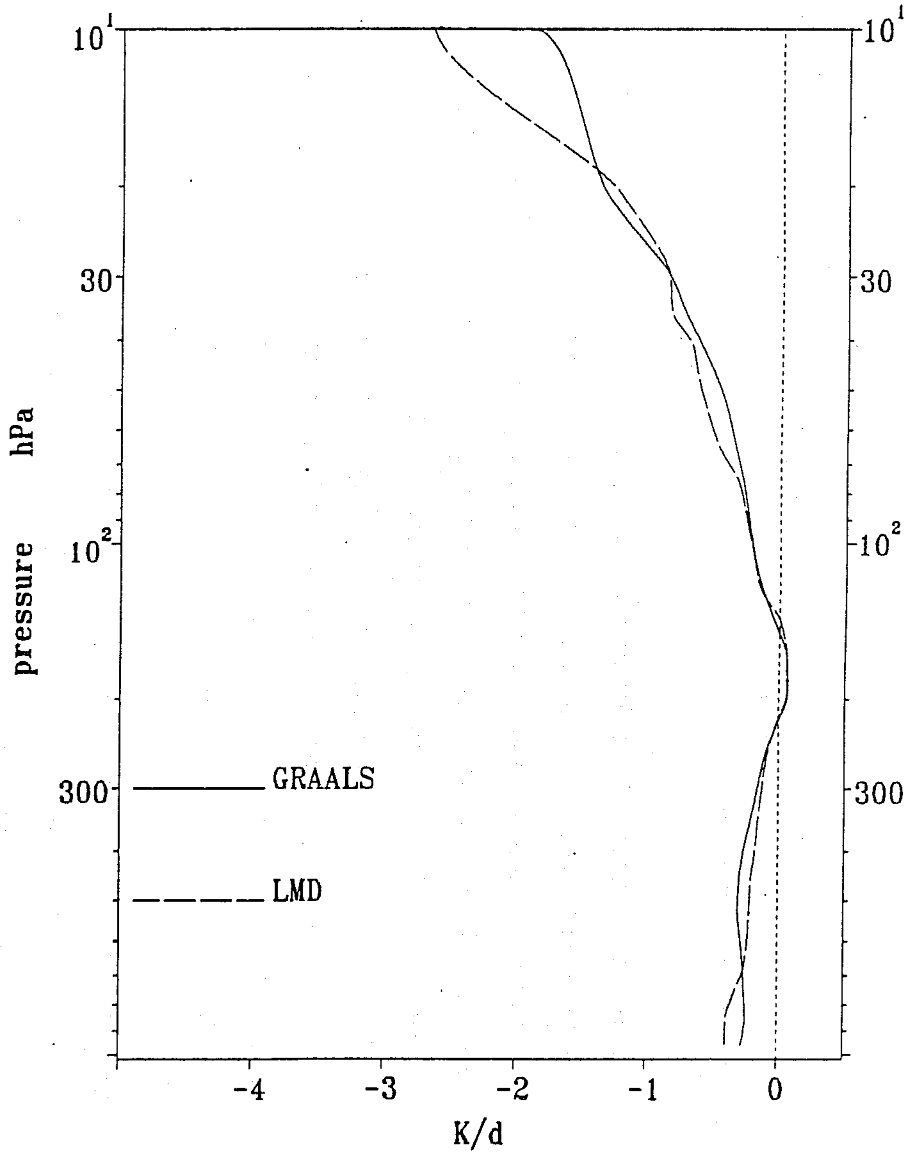

Fig.17: Same as Fig.16, but with the revised version of the DWD radiation scheme.

3.2 New concepts and approaches

The difficulties associated with standard validation methods discussed in the previous section instigated various attempts to develop new, more promising validation strategies. The concept of 'cloud radiative forcing' (CRF) provides a way to investigate the model's capability to simulate the overall impact of clouds on the radiative transfer process on regional and global scales. The CRF, which may be split in a solar and a thermal component, is defined as the difference between the fluxes for cloud-free conditions and those that are observed (or simulated) for the actual situation, including clouds. The determination of the CRF from satellite observations is straightforward for the cloudy fluxes as they correspond to the actual measurements. However, the cloud-free contribution in cloud covered regions has to be derived from spatial and/or temporal interpolation from observations which are classified as cloud free. Both the necessity to distinguish between cloud and cloud-free observations and the problems associated with the interpolation of observations are sources of uncertainty, which partly explain, why various satellite based estimates of the CRF show considerable disagreement. For the comparison with the corresponding model results, the method employed to obtain the equivalent quantities from the model simulation is also of relevance. In a model simulation one could obtain cloud-free fluxes either in a way similar to the satellite observations or, as is often done, by a recalculation of the fluxes at each gridpoint assuming cloud-free conditions. As demonstrated by *Cess and Potter* (1987), the choice of method is of considerable importance for the values of the modelled CRF and may therefore complicate a comparison with satellite based estimates or among models. A further disadvantage of the CRF for the purpose of NWP model validation is the fact, that for NWP models errors in CRF determined at the top of the atmosphere are not as crucial as an erroneous partition of the forcing between the atmosphere and the earth's surface. In particular the solar CRF, which affects mostly the surface energy budget, could be wrongly simulated over oceanic areas without detrimental consequences for the model evolution, since the fixed sea surface temperature implies an unlimited source or sink of energy. Furthermore, a comparison of 'observed' and modelled CRF in form of temporal and spatial mean values suffers from the same problems that were addressed in the previous section in the validation of radiative fluxes and cloud cover.

An investigation of the diurnal cycle of simulated and observed radiative effects at the top of the atmosphere was presented by *Vesperini et al.* (1992). As an example from this study, Fig.18 illustrates the monthly mean diurnal cycle of the OLR for July 1987 as observed from METEOSAT and as simulated with four versions of the ECMWF model, using different horizontal resolution. In the region for which the presented results are valid, i.e. the Sahara desert, there is obviously a marked positive bias in all model versions but the one with the lowest resolution. Cloud contamination as a possible, but unsatisfactory explanation for the better agreement at T21 was suggested. However, this would be in contradiction to the solar results (not shown), where at T21 the albedo was lower than at higher model resolution. Despite the large bias, a closer

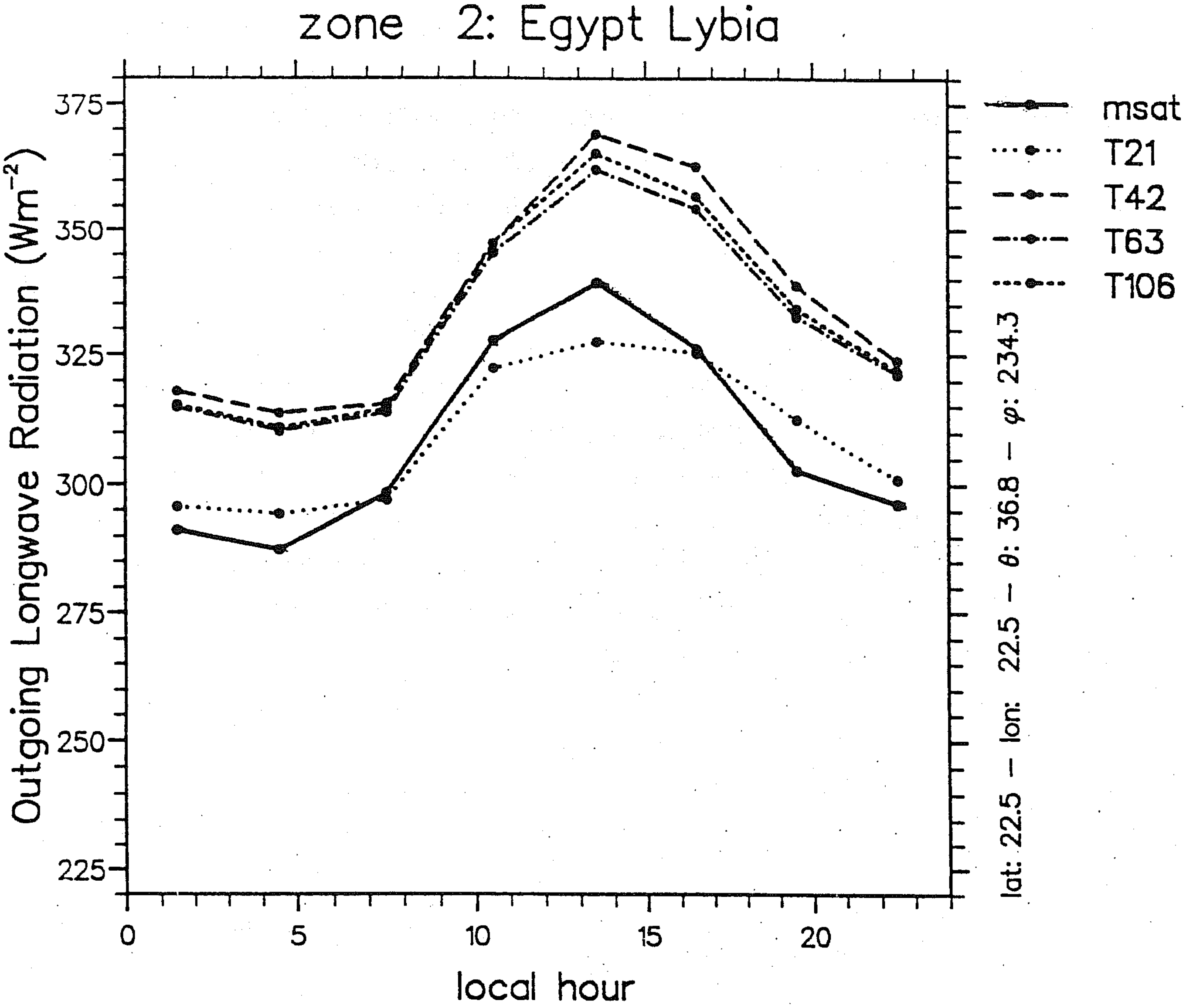

Fig.18: Monthly mean diurnal cycle of the OLR over the Sahara desert as observed from METEOSAT (msat) and as modelled with the ECMWF forecast model at various resolutions for July 1987. From Vesperini et al. (1992).

inspection of Fig.18 can reveal further interesting aspects. The temporal evolution of the observed and simulated OLR in this clear sky area mirrors the daily cycle of the surface temperature. The simulations, at least at higher resolution, capture the amplitude and the overall structure of the diurnal cycle very well, but exhibit a non-negligible phase lag. The fact, that this pase lag occurs both for the increase (daytime warming) and the decrease (night time cooling) suggests that the modelled thermal inertia of the surface-atmosphere system is too large. This problem could be linked to the parametrization of surface processes. The top layer mean temperature, which is employed as prognostic variable, responds necessarily slower than the skin temperature of the earth, which controls the emitted black body radiation of the surface. In other areas, in particular in the presence of clouds, the relation between specific model deficiencies and discrepancies highlighted by this kind of comparison is not always that obvious, since an integral property like the OLR (or the reflected solar flux) is the result of a complex interaction between model state (e.g. temperature, humidity, clouds) and intricate processes parametrized with varying degrees of accuracy. However, by the use of a whole selection of validation tools it is often possible to close in on the true cause of a problem.

Another validation method, which addresses mainly aspects of the evolution of clouds and radiation in a model simulation, was developed by *Morcrette* (1991). The so-called model-to-satellite approach is characterized by an adaptation of model output to satellite measured quantities. In contrast to other methods, where satellite measured radiances are converted by more or less complex algorithms to the same kind of products generated by forecast models (e.g. OLR, cloud cover, surface temperature), the core of this method consists of a model simulation of radiances in those spectral intervals, where satellite channels are located. On this basis, the model-to-satellite approach can be used mainly as a tool for the validation of cloud cover and other model properties relevant to the radiative transfer calculation. Aspects of radiative transfer itself are addressed only indirectly (e.g. via the cloud optical properties used), since the forward calculation represents only a small fraction of the spectral domain. Evolution histograms of observed and simulated brightness temperatures present one way to evaluate the results of this technique. In accordance with the results of the OLR comparison discussed before, Fig.19a and b demonstrate also the existence of a phase lag in the modelled surface temperature evolution. In the absence of clouds, atmospheric effects are only of minor importance in the considered spectral region, i.e. the METEOSAT window channel. For this reason, the model-to-satellite approach provides an even clearer indication that the phase lag is related to a problem in the simulation of surface temperatures. A bias in the window channel brightness temperatures is evident in the daytime maximum, but it is of opposite sign compared to the bias seen in the OLR validation. An overestimation of atmospheric absorption in the window region in conjunction with an exaggerated transparency of the atmosphere in the region of the major gaseous absorption bands could be a potential explanation for this seemingly contradictory result.

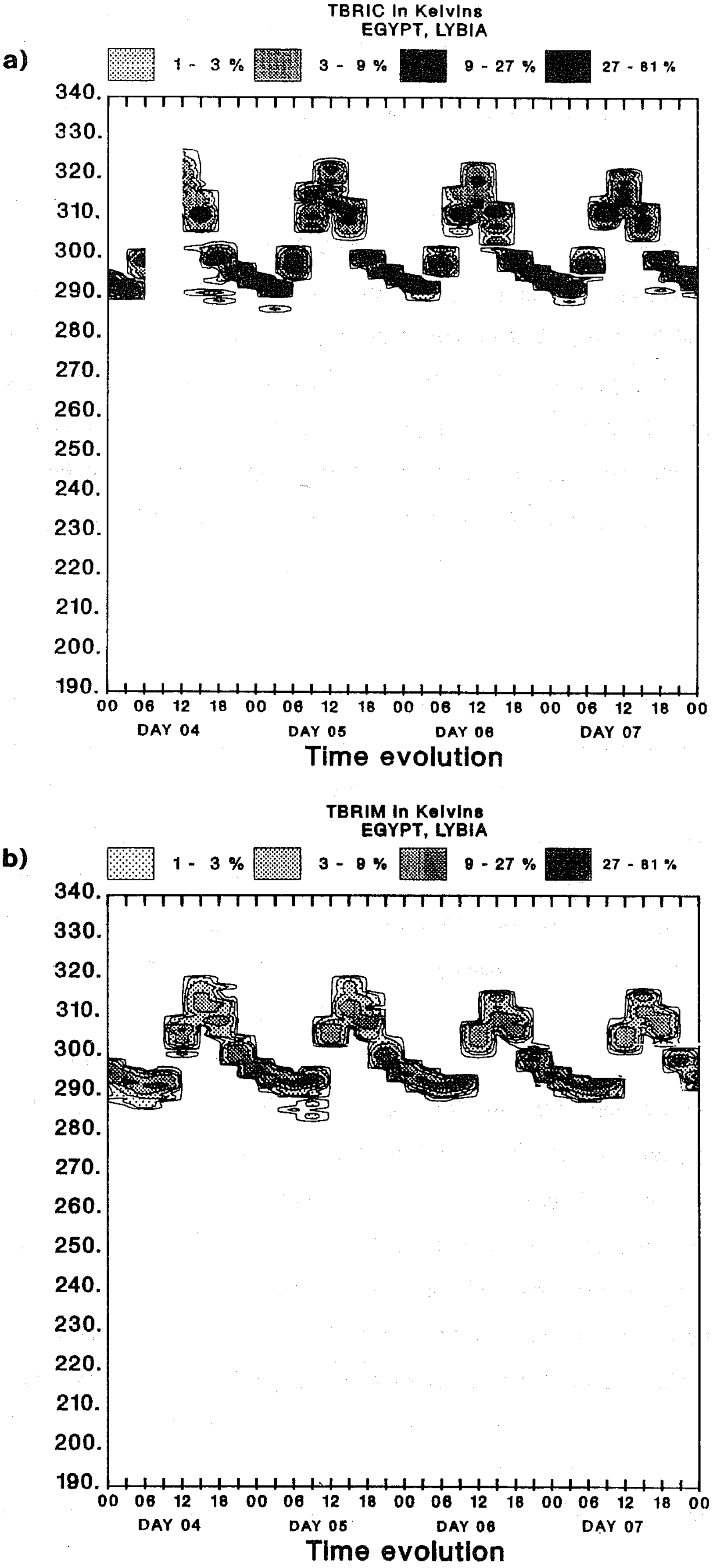

Fig.19: Evolution histograms of the observed (a) and modelled (b) brightness temperature in the atmospheric window channel of METEOSAT for the Egypt-Lybia region. From Morcrette (1991).

In a cloudy region like central Africa the method provides insight in the models ability to represent the impact of clouds on the radiative transfer. As shown in Fig.20a,b, in regions of strong convective activity, the amplitude of the diurnal cycle, indicated by the evolution of the maxima in brightness temperatures, is very much reduced. It is also very evident, that the model fails almost completely to simulate the impact of the daily variation in convective cloud cover and cloud top height on the minima in the brightness temperature. This clear demonstration of a model's deficiency to simulate a physical process is a main strength of this approach. In conventional temporal and/or spatial mean comparison exercises this kind of problem becomes hardly, if at all evident. However, the relation of the problem to it's physical cause remains still a formidable task, that can only be undertaken in conjunction with other validation methods. In this particular example, the deficiency could in principle be caused by a lack of convective clouds or by a severe underestimation of their vertical extent or their optical thickness, which itself is related to the cloud liquid water path.

An example of a process validation study of more relevance to climate simulations than to NWP is presented by *Randall and Tjemkes* (1991) for the Colorado State University GCM. The so-called greenhouse factor, defined as the ratio of black body radiation emitted at surface temperature to the OLR is an overall measure of the atmospheric greenhouse effect. Both OLR and sea surface temperature are readily available from satellite observations and model simulations, allowing a straightforward comparison. Plotting the greenhouse factor as a function of sea surface temperature (cf. Fig.21), both for clear sky and cloudy conditions, allows a more detailed examination of the model behaviour than looking at the global mean values. In the clear sky case model and observations agree rather well over a wide range of temperatures. A slight continuous increase of the greenhouse effect with temperature is an indication of the larger radiative opacity of the atmosphere in the presence of larger water vapour amounts, which occur mainly in tropical regions. At the high end of the temperature range the CSU GCM underestimates the clear sky greenhouse factor. As pointed out by Randall and Tjemkes, this might be related to a lack of moisture in the model or to a cloud contamination of the 'observed' quantity. In that respect, the derivation of the 'observed' clear-sky greenhouse factor from the original satellite measurements is affected by the same 'declouding' problems as the CRF. In the cloudy case, where model results and observations are more directly comparable, the agreement is surprisingly good over a large part of the temperature range. The dramatic increase of the green house factor for high temperatures is caused mainly by deep convective clouds in tropical regions. This effect is by far overestimated in the CSU GCM, but no explanation of this deficiency is provided.

4. CONCLUSIONS AND OUTLOOK

A detailed knowledge and understanding of the model evolution and it's deviation from reality is essential for any further progress in the field of numerical weather prediction and climate simulations. However, for

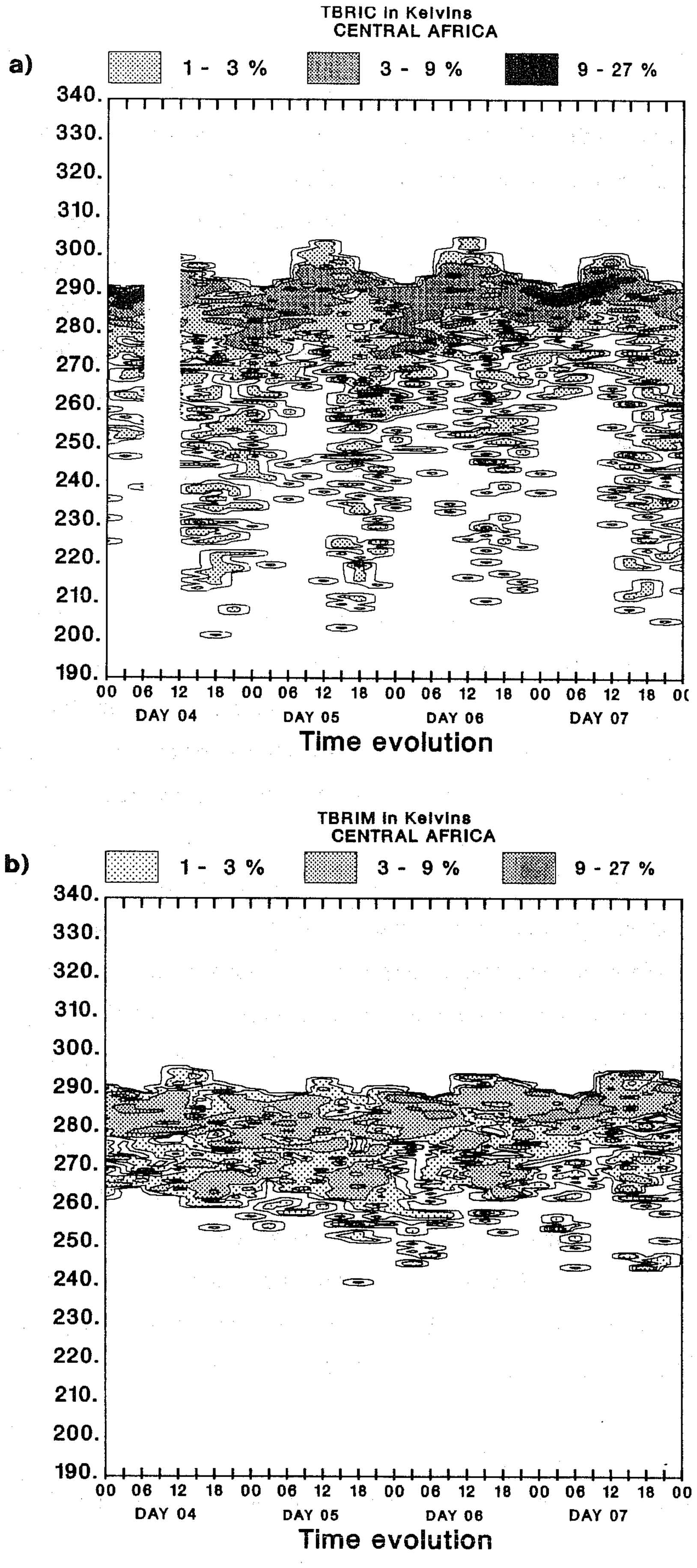

Fig.20: same as Fig.19 for a central african region. From Morcrette (1991).

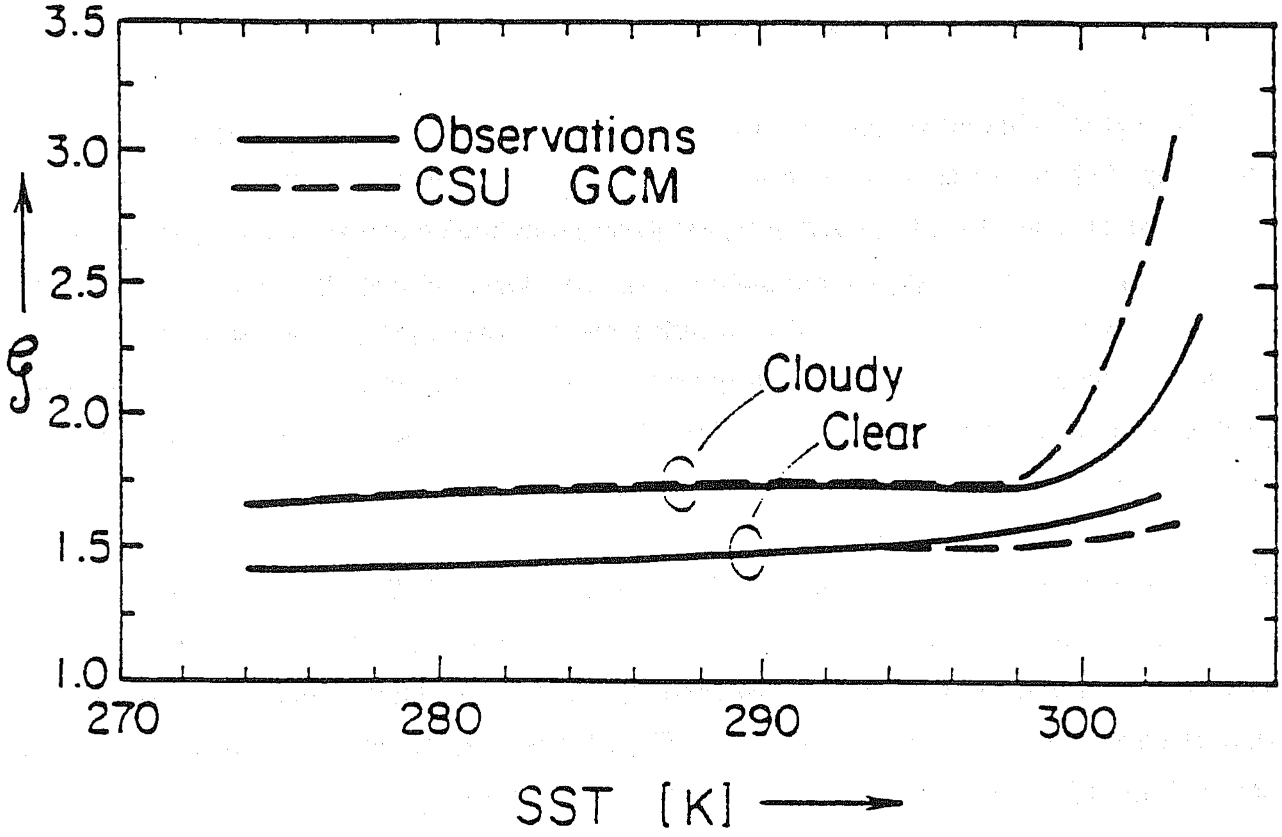

Fig.21: Plot of the greenhouse factor as function of see surface temperature for the CSU GCM and from satellite observations. From Randall and Tjemkes (1991).

radiation and clouds, just as for any other component of an atmospheric model, the complexity of the processes, the sparsity and lack of reliability of adequate observational data and the limitations of our insight in to the matter are severe obstructions of this aim.

From the selection of examples discussed in this paper it should be obvious that an improvement in number and quality of observational datasets relevant to the task of model validation is one of the key issues for further progress in the field. The development and judicious application of new validation methods has the potential to partly close the gaps in the observations. The largest potential for model improvement lies probably in those validation tools that allow an insight into the models ability to represent processes rather than model (mean) states. However, it will generally remain rather difficult to relate a diagnosed model problem to a particular cause in the model configuration. For this purpose, it will often prove beneficial to look at the results of different validation methods simultaneously.

Finally, one should be aware that the validation of any part of an NWP is a continuous effort. Any modification in one area of the model will have an impact of some degree on all other aspects of the model. An insufficient monitoring of the model could imply that we spoil one aspect of the model behaviour by the introduction of an improvement in other regions. There is a real danger, that this effect prevents the long term evolution of the NWP from convergence to the atmospheric reality.

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