VALIDATION OF THE FORCING IN THE ECMWF MODEL

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1. INTRODUCTION

Already in the early stages of the model development at ECMWF the important role of diabatic forcing for the prediction of the large scale flow has been realized. Since then much effort has been devoted to improve the parametrization schemes like those for cumulus convection, vertical diffusion, surface processes and radiation. Also new schemes for shallow convection and gravity wave drag have been added to complete the representation of sub-grid scale processes.

The validation of the output of revised or new parametrization schemes has always been a difficult task due to a general lack of observational data. Field experiments like GATE, ATEX, etc. were useful for the validation of cumulus convection. However, even comprehensive measurement campaigns like GATE have only covered a limited selection of circulation types. The data is not sufficient to validate cumulus convection for all possible conditions. Similar arguments are true for other parts of the parametrization package, especially for the parametrization of surface fluxes. For the validation of radiation fluxes at the top of the atmosphere the situation is much better. High quality measurements from the Earth Radiation Budget Experiment (ERBE) allow a direct comparison against model output values and the very important process of cloud-radiation interaction can be validated by comparing clear sky fluxes with cloudy fluxes. In this context the comparison of model clouds with observation plays an important role in the forecast verification. For a global comparison cloud data form the International Satellite Cloud Climatology Project (ISCCP, *Rossow and Schiffer*, 1991) is available.

Diabatic forcing can be calculated from the large scale residual of the tendency equations for temperature, wind and moisture by using the operational analysis. When comparing these estimates with the forcing from the model, shortcomings in the parametrization schemes can be revealed (*Klinker and Sardeshmukh*, 1992). However, diabatic heating rates derived from analyses are not completely model independent. Especially in data sparse areas the diabatic forcing produced by the parametrization schemes has a strong influence on the analyzed flow field via the six hour forecast that serves as a first guess for the analysis. However, in data dense areas like over Europe the information of observations entering the analysis should to be sufficient to estimate long term averages of diabatic forcing.

The quality of the numerical prediction models has been improved to such an extent, that short range forecasts in data dense areas have become almost as accurate as observations. Therefore small deviations of six hour forecasts from observations may help us to understand deficiencies in the diabatic forcing. Following this line of error diagnostic we have to be aware that errors in the diabatic forcing induce an adjustment process that may weaken or change the error signal. For instance adjustment to thermal forcing errors could induce errors in the wind field.

2. DIRECT VERIFICATION OF RADIATION FLUXES

The availability of high quality measurements for radiation fluxes from ERBE at the top of the atmosphere has offered the opportunity to validate radiation schemes of large scale models on a global scale. The accuracy of monthly mean measurements in the order of 10 W/m^2 for regions (*Barkstrom,* 1984) is sufficient to detect model errors. However, the time consuming post processing of some observations taken by satellite borne instruments reduces the usefulness in an operational forecast environment. For the validation of the current model formulation observational data not older than a few weeks or months is needed.

However, there is one solution to the problem of not delaying the validation of a new model formulation and still using high quality observational data. That is to rerun the data assimilation for a period of a good data coverage and using the latest model cycle. At ECMWF the data for July 1987 has been reanalysed, as for this period daily ERBE radiation fluxes and ISCCP cloud information were available. In this data assimilation experiment a system was used in which the model and the analysis formulation dated from July 1991.

Additional to the net short wave and long wave radiation flux at the top of the atmosphere, clear sky fluxes have been derived from the observational data in areas where enough cloud free pixel could be found. This is sometimes not possible, especially in the tropical convergence zone where cloudy conditions prevail throughout the month. In the model the calculation of clear sky fluxes and total fluxes is more straightforward. The radiation transfer equation is solved under the assumption of cloud free conditions and then repeated with the clouds diagnosed in the model. The cloud forcing is then defined as the difference between the clear sky fluxes and the fluxes for cloudy conditions. Differences between the calculation of clear sky fluxes from observations and from model values introduce errors into the comparison of observation and model simulation of cloud forcing. However, the results show quite large signals in the differences of the cloud forcing, suggesting some real model problems.

As cloud-radiation interaction is a process of high importance for a correct parametrization of diabatic forcing by radiation, a validation of clouds is necessary as well. A global data set of cloud coverage for July 1987 is available from the ISCCP cloud data products. Here in this study we restrict the validation to cloud cover, though this can only be a first step as variations in cloud optical properties are important for the cloud-radiation interaction. Total cloud cover is a parameter that can be used for a model verification with little reservation, whereas high, medium and low level cloud cover depends very much on how the boundaries in the classification are defined. Therefore differences between the model clouds and observed clouds can partly be due to discrepancies of the model cloud scheme and the ISCCP-definition.

2.1 Validation of short wave fluxes

The difference between the model and observed short range fluxes at the top of the atmosphere show two distinctive large scale features (Fig. 1a). Over the Mediterranean Sea and the Black Sea a negative model bias suggests quite a large overestimate of the reflection of solar radiation. That these differences are due to deficiencies in cloud cover are obvious and readily supported by comparing the observed and model produced cloud forcing for the short range band (Fig. 1b and c). The short wave cloud forcing in the model is up to 160 W/m^2 larger than the observations suggest. The problem over the Mediterranean arises from an unrealistic low level cloud cover. This appears as a remarkable positive model bias when the low level model cloud cover is compared against ISCCP data (Fig. 2d).

Over continental parts of Europe and the North-West Atlantic we find again a good correlation between a model bias in the cloud cover and a model bias in the short wave radiation fluxes. Insufficient cloud cover in these areas explains the underestimate of cloud forcing and a surplus of absorbed solar radiation that increases the net downward flux of solar radiation at the top of the atmosphere.

2.2 Validation of long wave fluxes

The model bias of OLR compared to ERBE observations is much smaller than the differences in the short wave range (Fig. 3a). The sign of the bias is in the direction to compensate partly the radiation bias in the short wave range. However the problem of spurious cloud cover over the Mediterranean has almost no effect on the long wave cloud forcing. The spurious clouds occur at low levels (Fig. 2d) where the cloud top temperature differs only by a relatively small amount from the surface temperature compared to a bias that would arise from spurious clouds at higher levels.

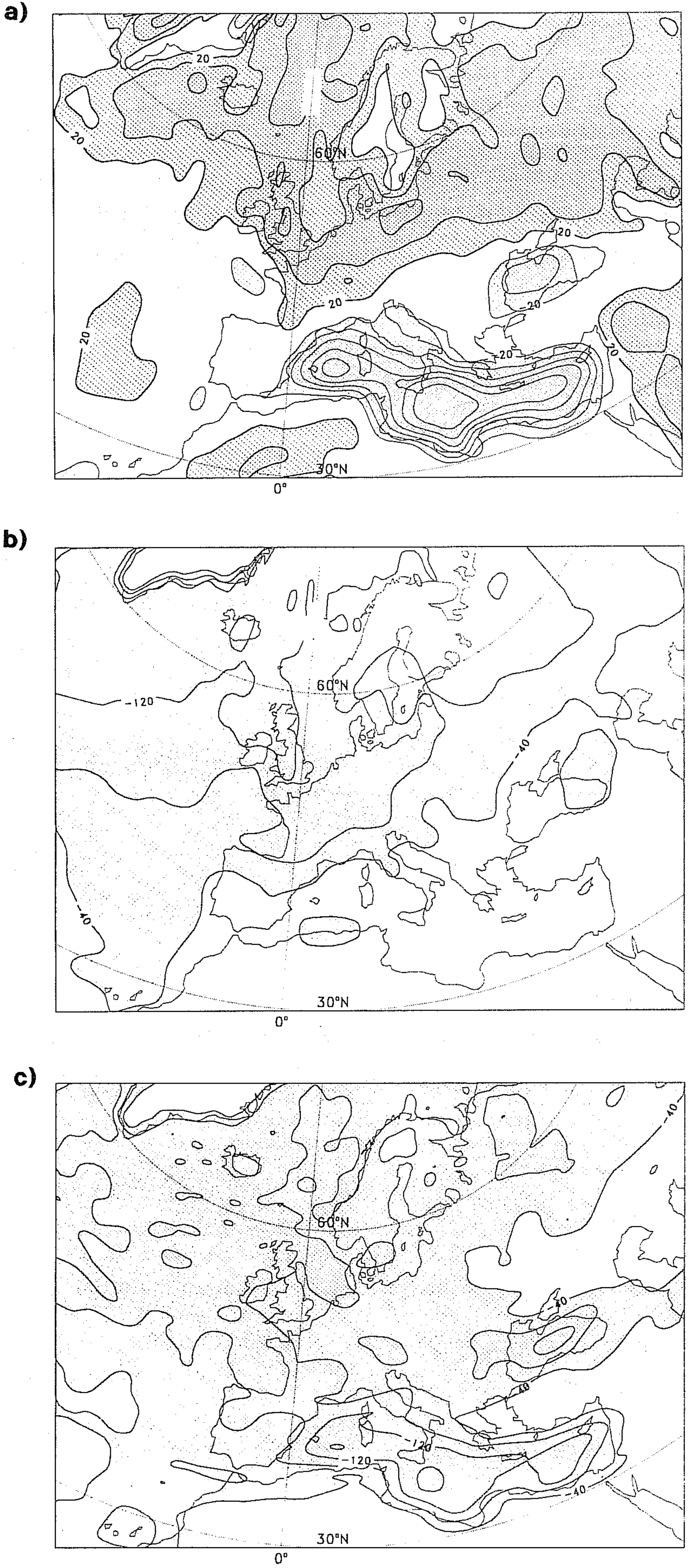

Fig. 1 (a) Top short wave radiation July 1987 (24 hour Model forecast minus ERBE measurements), Units W/m². (b,c) Short wave cloud forcing. (b) ERBE, (c) 24 hour model forecast, Units W/m².

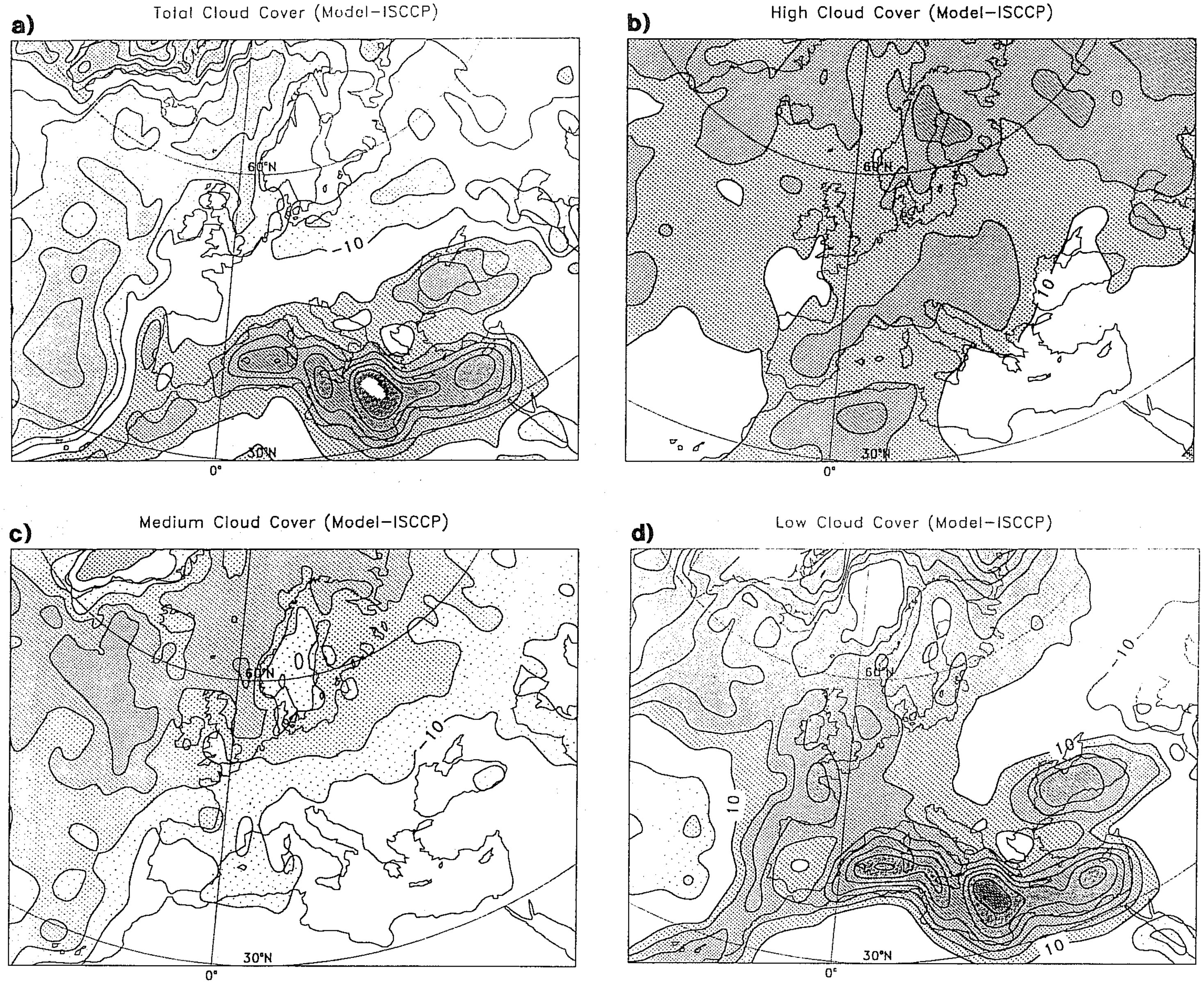

Fig. 2 Cloud cover, 24 hour model forecast - ISCCP observations. (a) total, (b) high level, (c) medium level, (d) low level cloud cover.

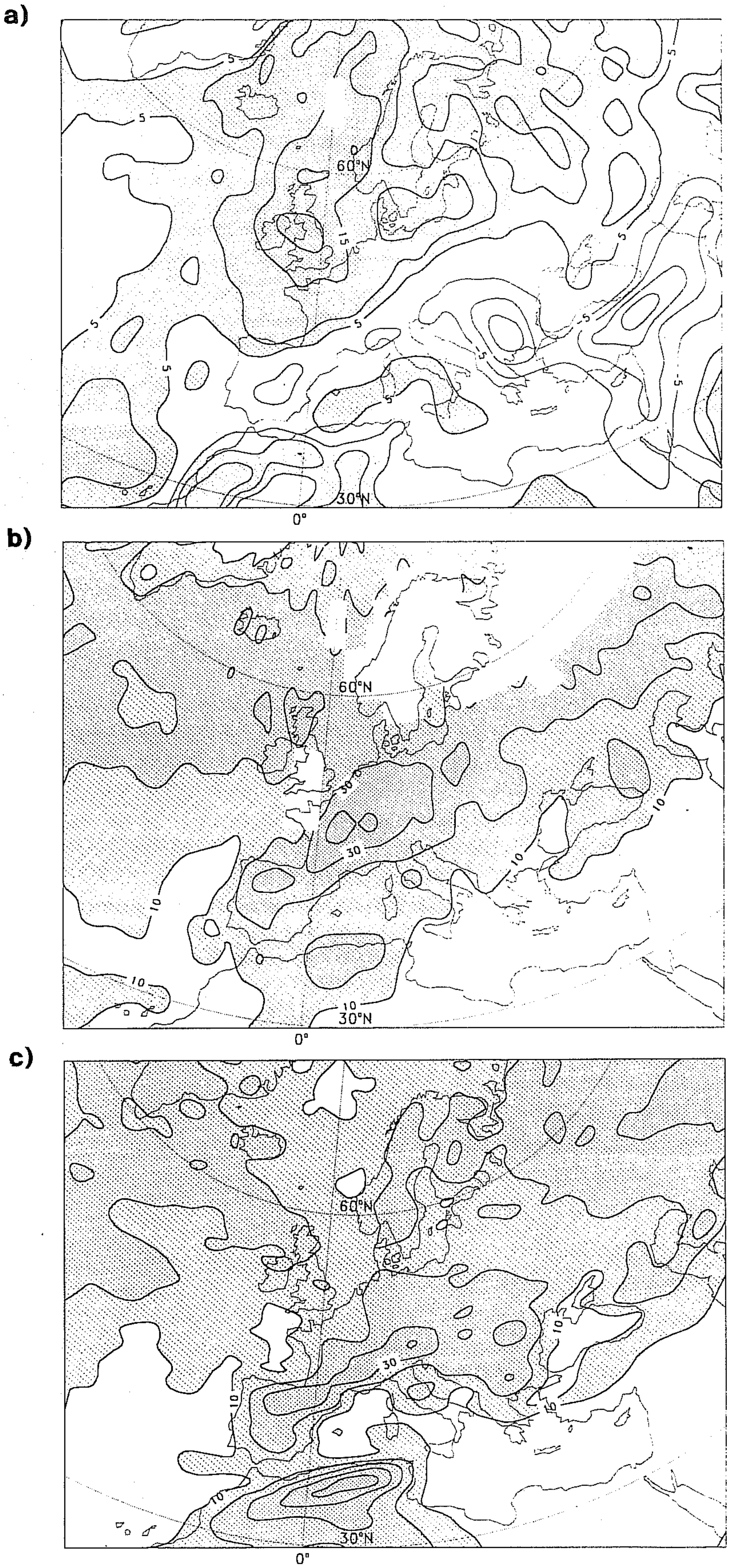

Fig. 3 (a) Top long wave radiation July 1987 (24 hour Model forecast minus ERBE measurements), Units W/m^2.
(b,c) Long wave cloud forcing. (b) ERBE, (c) 24 hour model forecast, Units W/m^2.

Insufficient cloud forcing for long wave radiation over higher latitudes of Europe corresponds to a surplus of long wave radiation escaping into space. The validation of clouds suggests that cloud cover is underestimated in the model. Whether there is lack of medium level clouds as shown by the validation against ISCCP clouds is not quite clear. Middle level clouds in the ISCCP data set are defined between 440 and 680 hPa and in the ECMWF model from $\sigma = 0.45$ to $\sigma = 0.8$. It is also possible that the model underestimates low level clouds. Daily validation suggests a general lack of shallow convective clouds in the summer.

3. VALIDATION OF FORCING USING BALANCE REQUIREMENTS

The large scale analysis of all atmospheric parameters can be used to evaluate the required diabatic forcing of subgrid scale processes from the residual in the tendency equations. Normally this is done from pressure level data, however, more an accurate and consistent way would be to use the model to calculate the initial adiabatic tendencies and average them over a long period. The indirectly derived diabatic forcing can then be compared with the forcing produced by the model parametrization scheme, or alternatively calculating the difference between the models forcing and the derived forcing. The difference between the two is, however, equivalent to adding the initial adiabatic and diabatic model tendencies. Even simpler: by calculating the monthly mean initial model tendency of a forecast variable we obtain the budget residual for that variable.

For July 1992 special model runs have been done in which all components of the diabatic forcing and the adiabatic tendencies have been saved. Here the tendencies are taken from the first to the second hour of the forecast. This has some advantages over using the tendency from the first hour especially with respect to the interaction of radiation and convection. During the first hour the radiation scheme does not have the information of the vertical distribution of convective clouds.

The zonal mean of the sum of the diabatic tendencies is shown in Fig. 4a. In the monthly mean these tendencies should be balanced by the adiabatic tendencies (Fig. 4b). However, differences are fairly large, especially at upper levels. The budget residual, which is the sum of the adiabatic and diabatic tendencies shows predominantly negative values (Fig. 4c). The question of how representative the errors from initial model tendencies are can be answered by comparing the budget residual with 5-day forecast errors (Fig. 4d). The general structure of the zonal mean temperature errors at this forecast range is similar to the structure of the budget residual. Particularly the negative budget residual below the tropopause develops into a similar 5-day forecast error.

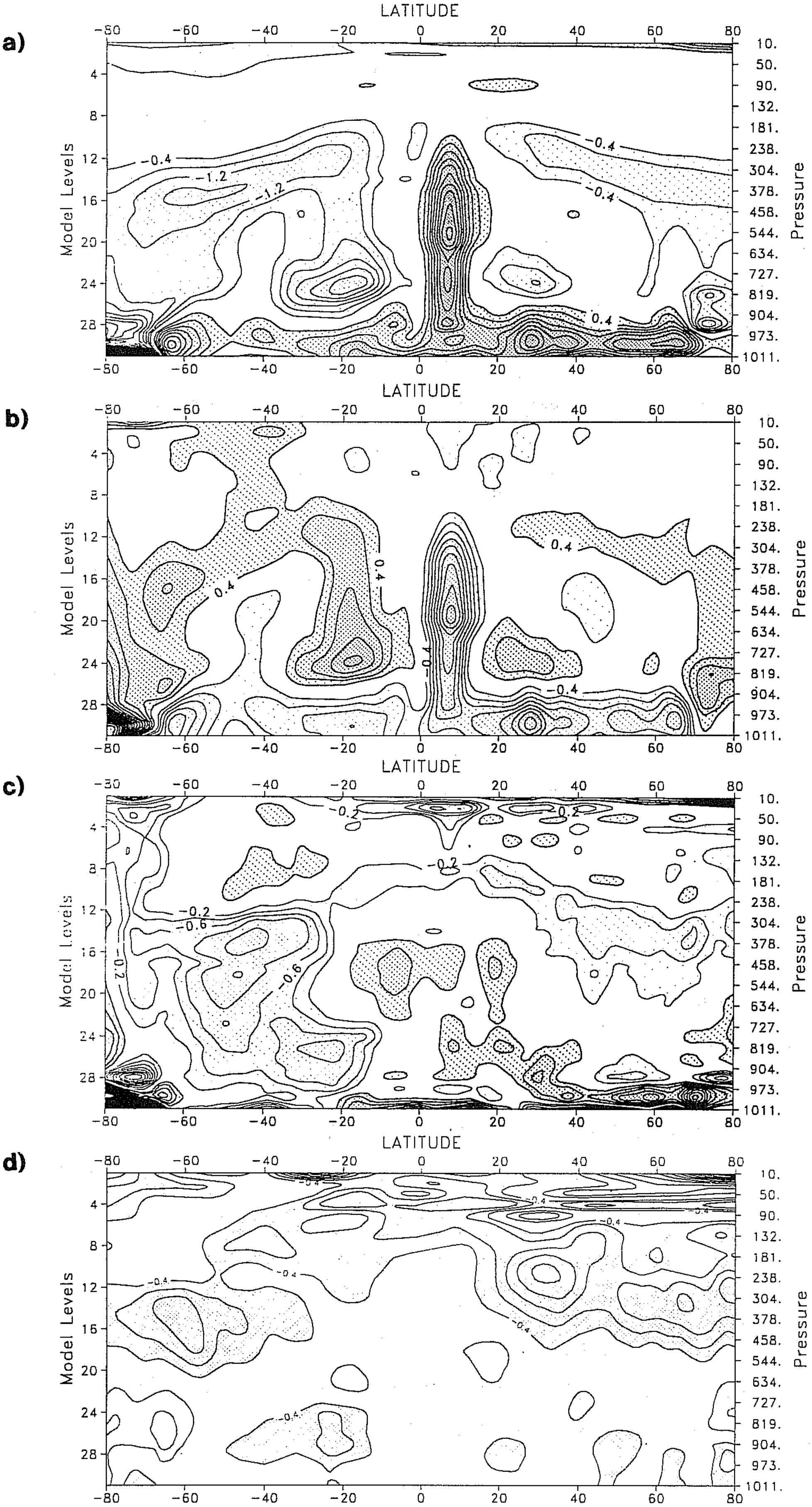

Fig. 4 Zonal and monthly mean temperature tendencies for the second hour of the forecast in June 1992.
(a) adiabatic tendency, (b) sum of all adiabatic tendencies, (c) residual = sum of (a) and (b). Units: K/day.
(d) 5-day forecast errors. Units: K.

The comparison of the residual with the contributions of the single processes to the diabatic forcing (Fig. 5 a to d) suggests some error causes. The negative residual at upper levels corresponds to strong radiative cooling below the tropopause and further below. A secondary residual in the Southern Hemisphere extra-tropics also coincides with large radiative cooling close to the top of the boundary layer.

In the tropics the strong diabatic heating by cumulus condensation is very closely balanced by adiabatic cooling of rising motion. As the data amount entering the analysis is not very large, even the small positive residual of up to 0.4 K/day could be an indication of too strong convective heating. The verification of rainfall from synoptic observations confirms this result. In most tropical areas or in the extra-tropics at times of strong convection the model overestimates convective rainfall.

In the extra-tropical storm tracks negative adiabatic temperature tendencies are not balanced by the condensational heating of large scale processes. It seems that the humidity in the analysis is underestimated, which results in insufficient large scale condensation rates in mid-latitude cyclones. The imbalance is reduced in a spin up process that adjusts the humidity field in the first twenty-four hours of the forecast to values closer to 100% relative humidity compared to lower values in the analysis. It seems that radiosonde observations have the tendency to create negative humidity increments over continents and coastal areas of the storm tracks.

Budget residuals for zonal means are very useful to identify first order forcing problems in the model on a large scale. The idea of defining the budget residual as a monthly mean of the initial model tendencies works here especially well as the observed monthly mean changes for zonal mean quantities are normally comparatively small. However, more information on specific forcing problems can be gained by investigating the budget for smaller regions. As stated below this approach will give best results in areas with a fairly good data coverage like Europe.

As an example the temperature budget of the boundary layer over Europe for the reanalysis period of July 1987 is discussed. Fig. 6a shows the diabatic heating averaged over model levels sixteen to nineteen, which is approximately the depth of the boundary layer. Diabatic cooling is the dominant process over most sea areas with up to 5 K/day over the Mediterranean and Black sea. Over the land areas warming is dominant with largest vales up to 6 K/day in eastern Europe. The main processes for producing cooling over sea are radiation (Fig. 7a) and for heating over land the turbulent fluxes of sensible heat (Fig. 7b). Adding up the monthly mean adiabatic and diabatic tendencies one expects

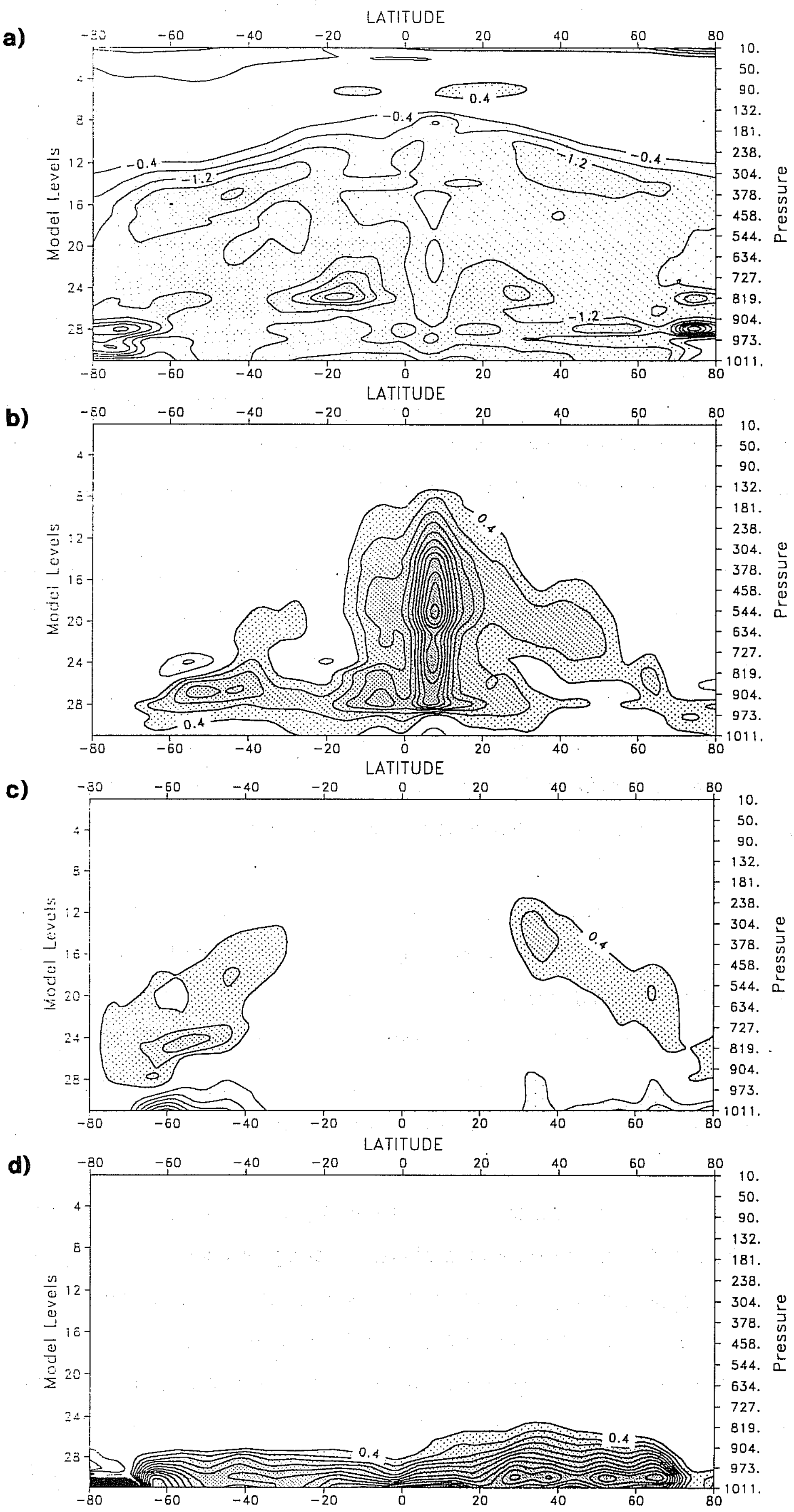

Fig. 5 Zonal and monthly mean temperature tendencies for the second hour of the forecast in June 1992. (a) radiative cooling, (b) heating from cumulus condensation, (c) heating from large scale condensation, (d) heating from vertical diffusion. Units: K/day.

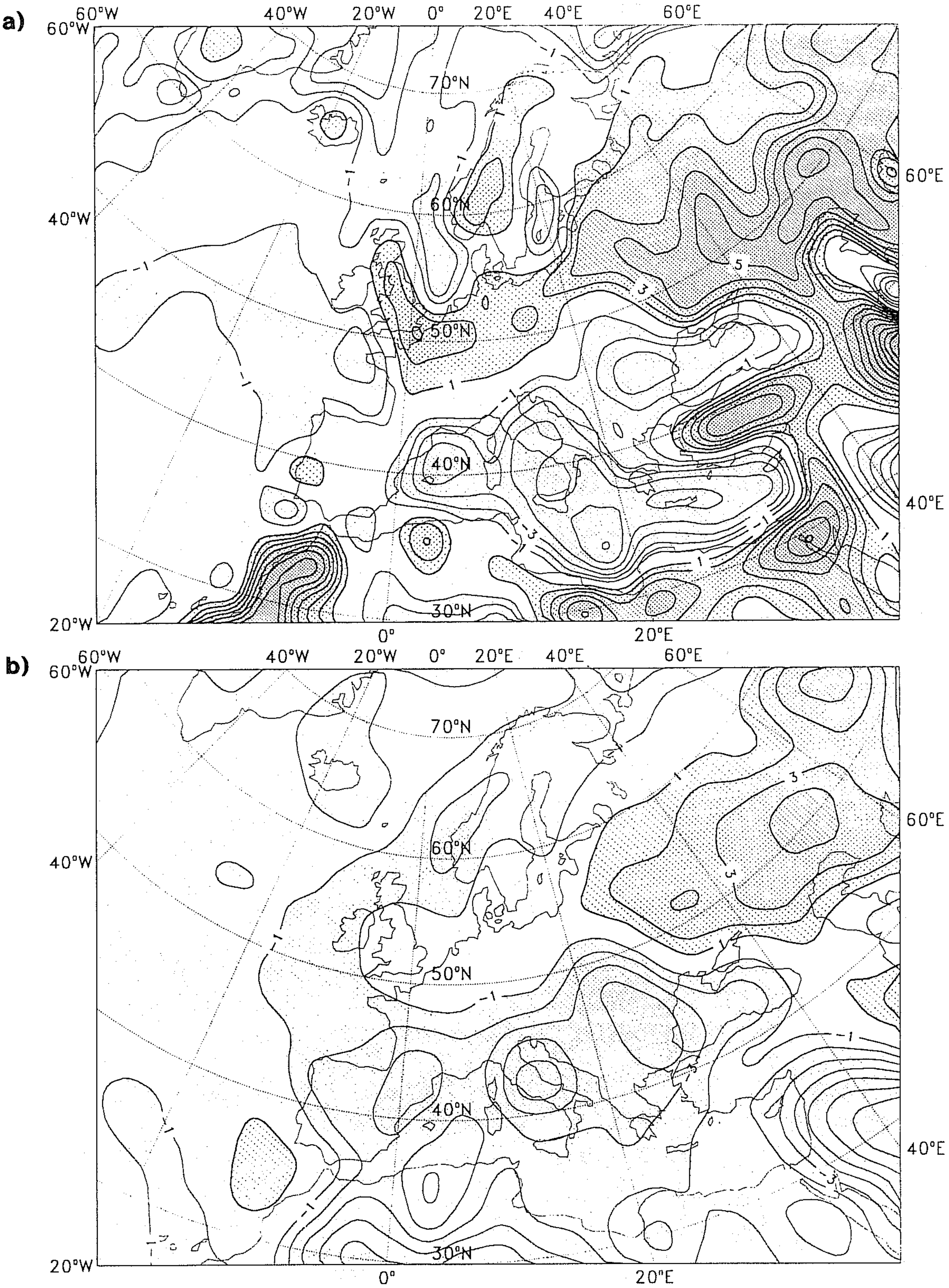

Fig. 6 Temperature tendency for the first hour of the forecast averaged over model level 16-19 (920-1010 hPa) for July 1987. (a) sum of all diabatic tendencies, (b) budget residual. Units: K/day.

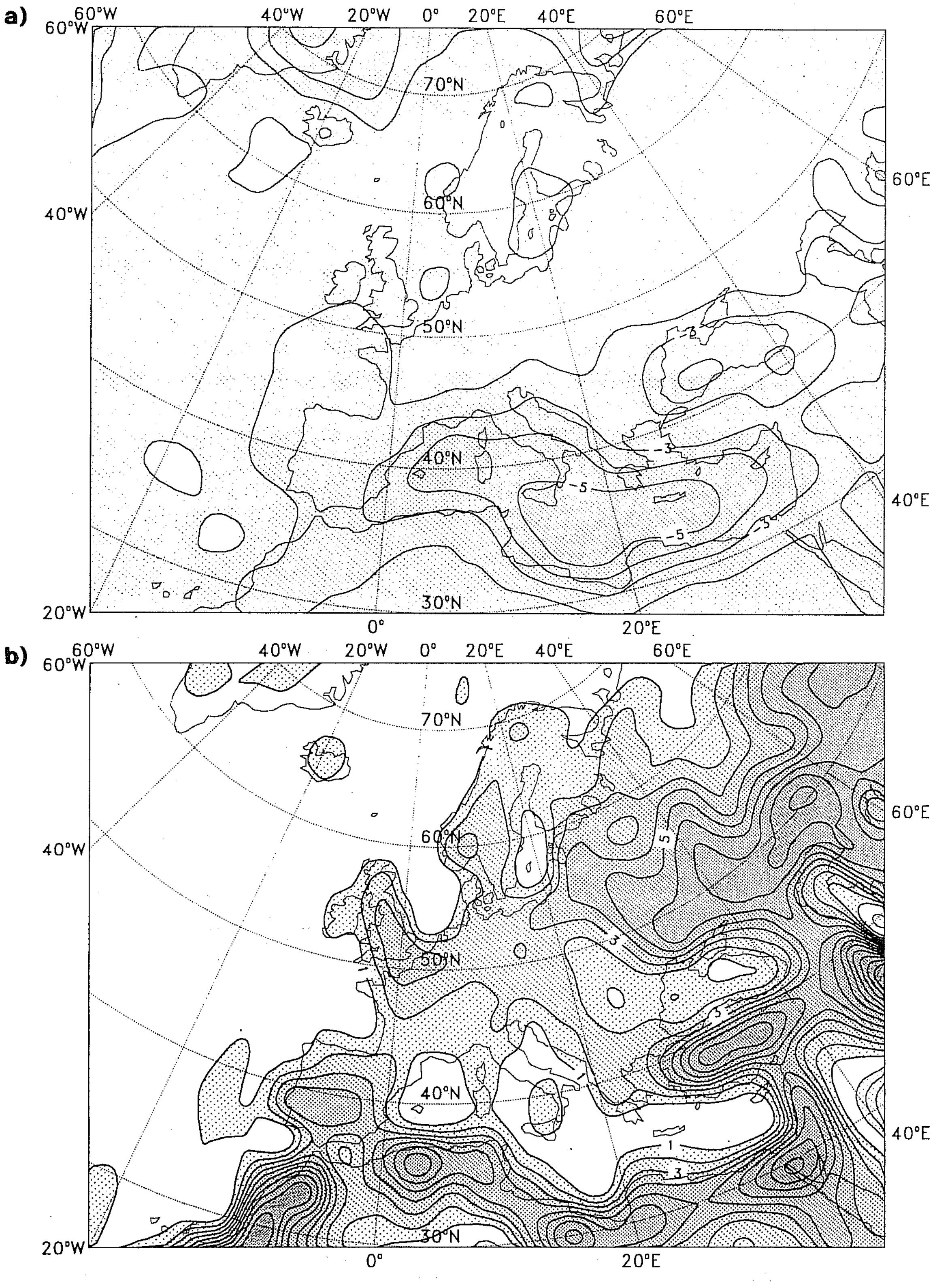

Fig. 7 Temperature tendency for the first hour of the forecast averaged over model level 16-19 (920-1010 hPa) for July 1987. (a) radiative cooling, (b) heating from vertical diffusion. Units: K/day.

rather small values as there should be a balance between the two components of the heat budget (Fig. 6b). However over large parts of the Mediterranean and the Black Sea the residual of the temperature budget is negative suggesting that the radiative cooling is too strong. The fact that the horizontal structure of the residual shows differences to the structure of the forcing is not surprising. Where the data coverage in the analysis is rather sparse most of the first guess information will be retained in the analysis. Then the residual in the budget can be fairly small even in the presence of an erroneous forcing. However, where the analysis draws to existing data of good quality, errors in the forcing will show up as a residual in the budget. Therefore we find a large maximum in the residual over Italy.

The problem of spurious clouds has been identified from the validation of cloud cover and short wave cloud forcing. By investigating the vertical structure of the negative temperature budget residual one can see that the spurious low level clouds produce a local temperature error as well. Fig. 8 shows a cross section of cloud fraction, radiative cooling and the budget residual for a Central Europe (average in east-west direction 0-20 degrees). The cloud cover is almost restricted to the second lowest model level. Here it creates strong radiative cooling of up to 7 K/day that can only be compensated partly by adiabatic warming, which results in a residual of around three degrees over sea. A modification to the occurrence of low level clouds has been introduced into the operational model in August 1992, which prevents low level inversion clouds to form in the lowest three model levels. This modification solved the problem of spurious low level inversion clouds in the Mediterranean.

The cloud related problem had such a pronounced impact on the diabatic processes in the Mediterranean that we were able to identify the problem with different approaches independently, either by using direct radiation measurements or an indirect budget technique. Other problems may need the complementary help from different techniques to obtain information of the causes.

Over the continental areas there is again a fairly good correlation between diabatic heating in the boundary layer and a positive budget residual of temperature. Over eastern Europe the residual is mainly positive suggesting that the turbulent flux of sensible heat is too large. Over the continental summer land masses a surface energy balance exists between the net absorbed radiation, the turbulent fluxes of sensible and latent heat and a small flux of heat into the soil. A surplus of sensible heat flux could arise from a wrong ratio between the latent heat flux and the sensible heat flux, especially when the soil is too dry. The validation of the solar radiation at the top of the atmosphere with the validation of clouds suggests that the absorbed solar radiation is likely to be too large due to the underestimate of clouds, possibly at medium levels.

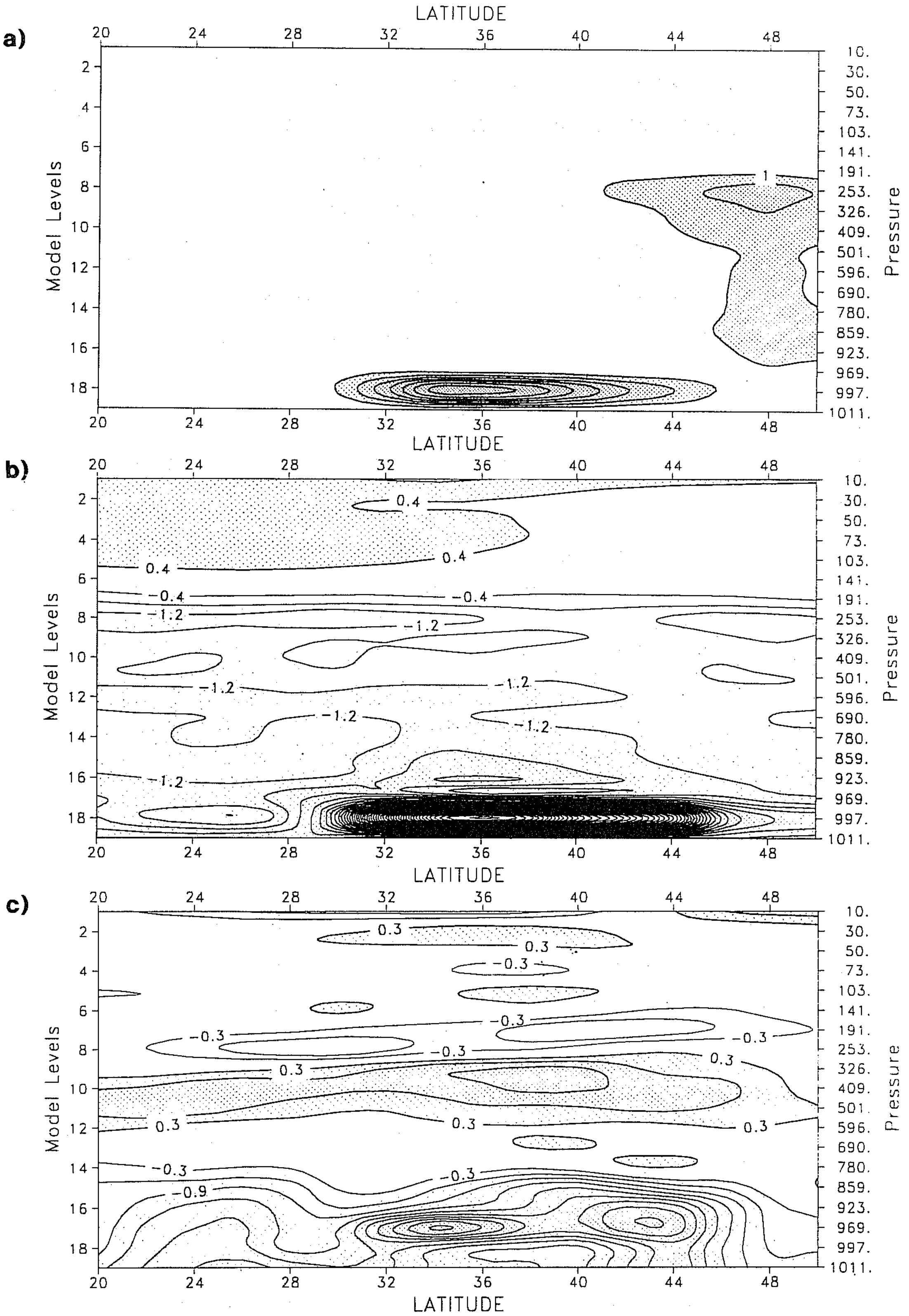

Fig. 8 Cross section over Europe for July 1987, average from 0-20 degrees east. (a) cloud cover, (b,c) Temperature tendency for the first hour of the forecast. (b) radiative cooling, (c) budget residual. Units: K/day.

4. VALIDATION OF FORCING USING SHORT RANGE FORECASTS

In areas of good data coverage like Central Europe there is normally a comparatively good fit of the six hour forecast to the observations. It is therefore worth investigating whether for certain cases when the diabatic processes are exceptionally strong, possible errors in the diabatic forcing show as short range forecast errors.

Strong convective activity was observed over Central Europe on 5 July 1992. Fig. 9a shows the total diabatic heating for the six hour forecast starting from the analysis at 6Z in the morning. Most of the heating arises from the cumulus condensation with values of more than 20 K/day in a region of widespread convection over Central Europe and three further but less intensive convective cells over eastern and northeastern Europe. The structure of the six hour forecast error verifying at 12Z suggests that convective heating produces errors of up to 8 K/day over Central Europe (Fig. 9b). Also the three further centres of large temperature errors correspond to maxima of convective heating.

A cross section over the small longitude band from ten to eleven degrees east shows the diabatic heating over Central Europe and the six hour forecast error of temperature (Fig. 10). The heating has two maxima separated by a minimum at a level at around 700 hPa. The minimum is due to the melting process below the freezing level. The six hour temperature error corresponds very much to the diabatic heating. The comparison of the heating and the error suggests that the overestimate of condensational heating is in the order of 50%.

When the convective heating is overestimated by a large amount like in this example, we can be quite confident in the interpretation of the first guess errors. However, we have to keep in mind the possibility of adjustment processes to excessive or insufficient forcing that may change the signal we finally see in the first guess error. This seems especially the case with processes that have a much shorter adjustment time than six hours. In *Klinker and Sardeshmukh* (1992) it was shown that excessive upper level east-west gravity wave drag over the Rocky Mountains created a south-north component in the 6 hour forecast error. The Fig. 11 shows the adjustment to diabatic wind forcing of the cumulus momentum transfer and the difference of the wind between a six hour forecast with and without momentum exchange. There is clearly a difference between the magnitude and the direction of the momentum exchange and its effect on the six hour forecast suggesting an adjustment of the flow to the momentum forcing.

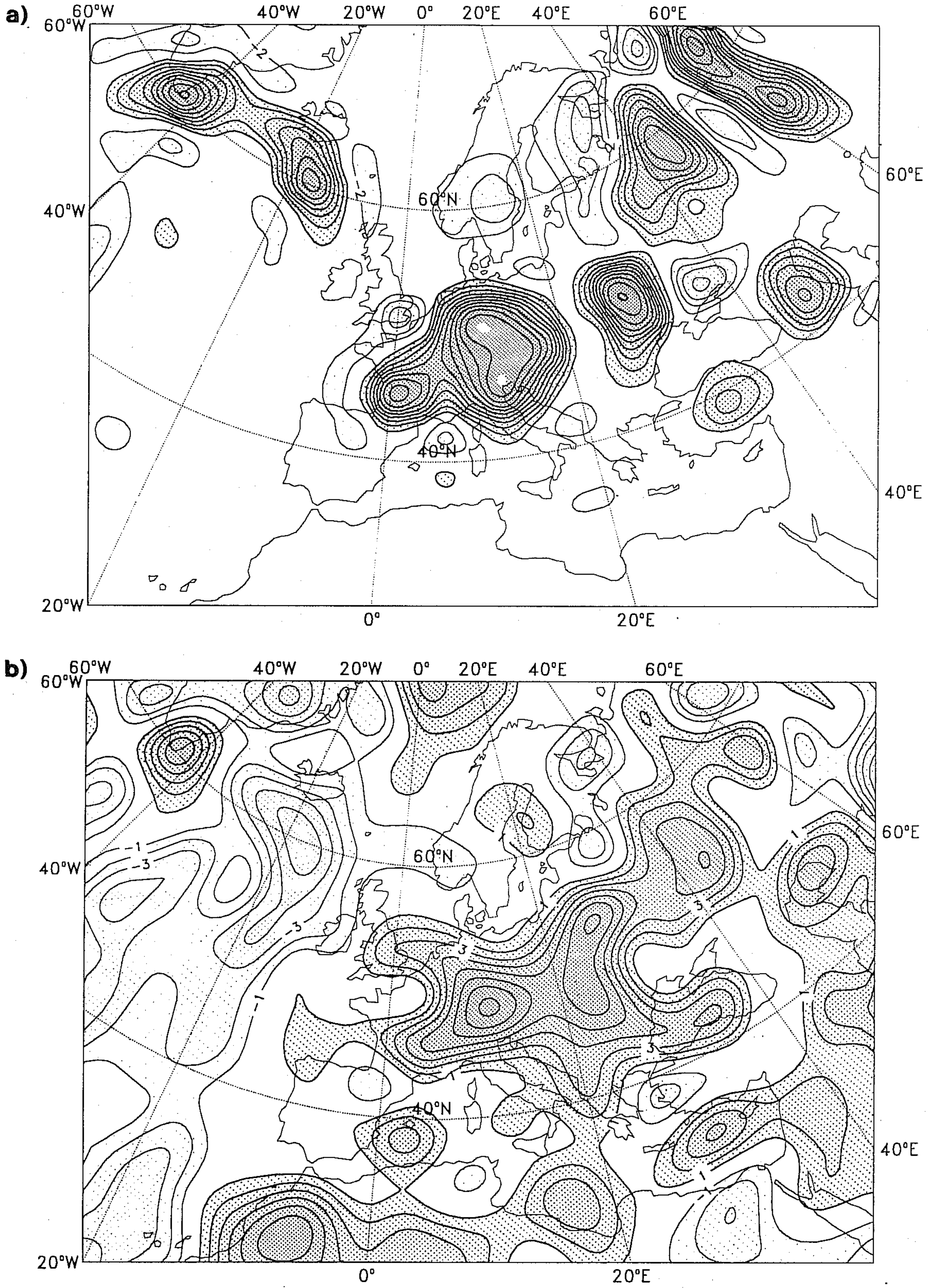

Fig. 9 (a) Sum of all diabatic tendencies for a six hour forecast form 5 July 1992 6Z. (b) 6 hour forecast error of temperature for 5 July 1992 12Z. Vertical average over model levels 22-23 (680-730 hPa), Units: K/day.

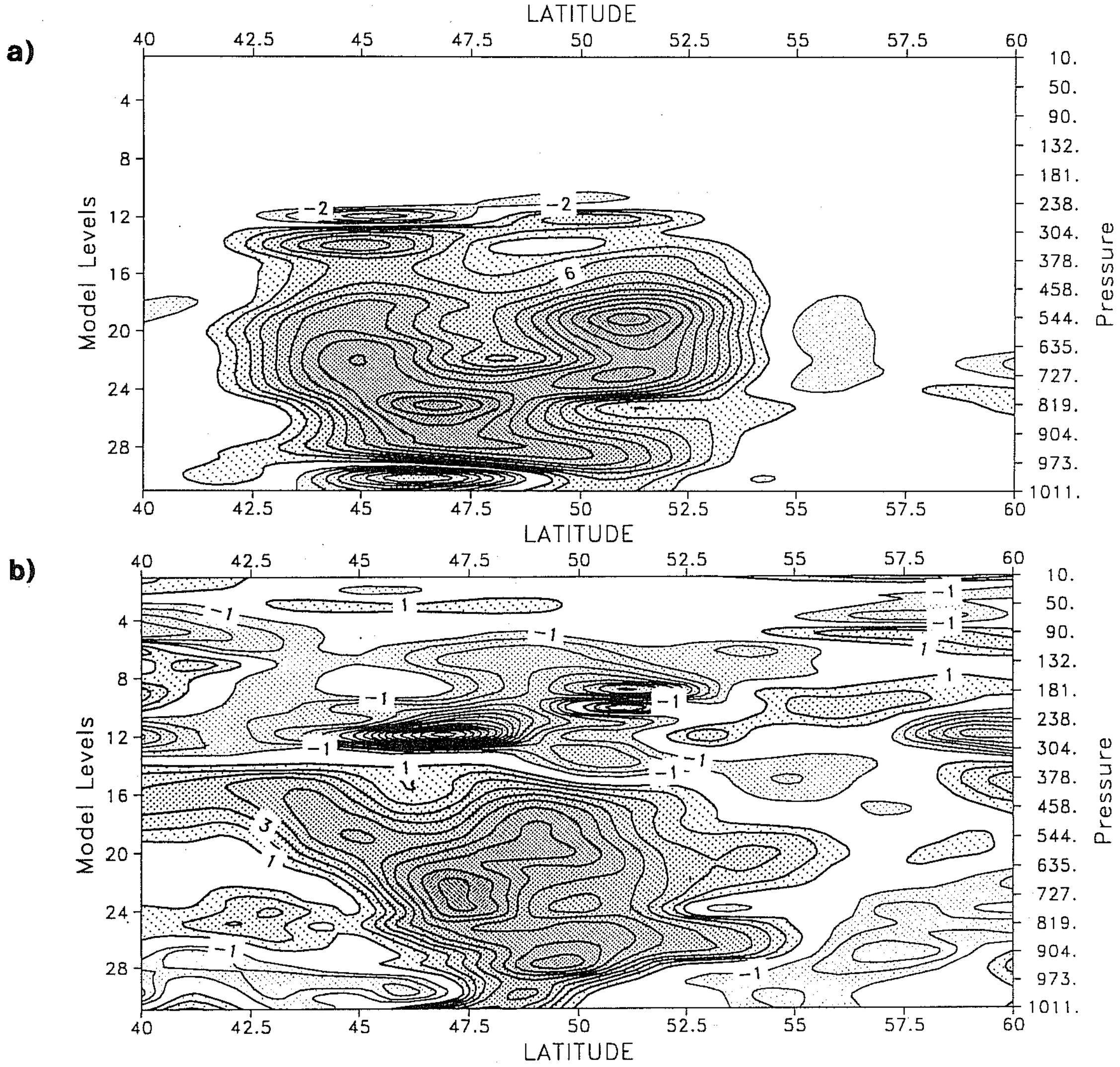

Fig. 10 (a) Sum of all diabatic tendencies for a six hour forecast form 5 July 1992 6Z. (b) 6 hour forecast error of temperature for 5 July 1992 12Z. Vertical cross section, zonal average from 10 to 11 degrees east, Units: K/day.

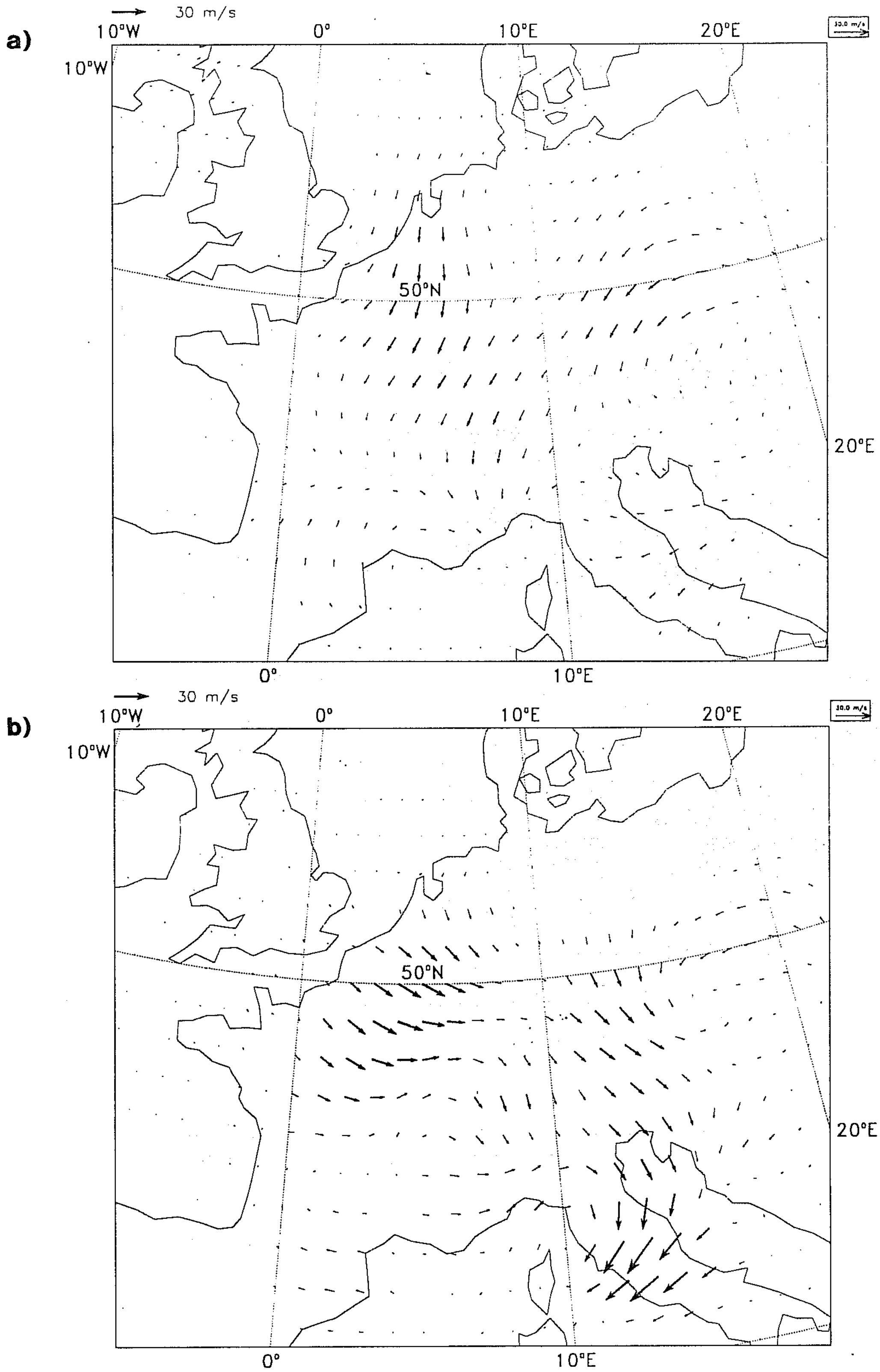

Fig. 11 (a) 6 hour forecast tendencies of wind, difference between run with and without cumulus momentum exchange. (b) diabatic wind forcing from cumumlus momentum exchange. 5 July 1992 12Z, model level 13 (304 hPa). Units: m/s/day.

5. SUMMARY

For the validation of diabatic forcing processes the amount of observational data is generally insufficient. Only for some aspects of the diabatic forcing there are observations that can be used for global validation. Especially the combined use of ERBE radiation measurements and cloud information from ISCCP has contributed to a better understanding of deficiencies in the cloud-radiation interaction of the current ECMWF model. However further experiments with data assimilation and forecasts had to be carried out to make the most efficient use of these types of data, which are normally not available in real time.

One rather large local forecast problem was the generation of spurious low level clouds in the Mediterranean during summer. This problem could be identified from reduced model solar radiation fluxes at the top of the atmosphere compared to ERBE data, a bias in the cloud forcing and an overestimate in the cloud cover when validated against ISSCP data.

To a certain extent the gap of observational data for validation can be filled by using global analysis data for the mass and wind field to derive the diabatic forcing and compare it with the forcing produced by the model parametrization scheme. The advantage of investigating the balance between large scale advection and diabatic forcing from initial model tendencies is obvious, more exact information on deficiencies in parametrization schemes can be gained. Though the budget of atmospheric state variables in the short term forecast range can be contaminated by spin up problems, experience has shown that budget residuals are to a large extent representative of medium range forecast errors. The application of this technique in June 1992 shows excessive radiative cooling rates at different levels of the atmosphere, a nearly global bias at upper levels below the tropopause and a bias close to the top of the subtropical boundary layer. The problem of spurious low level cloud cover in the Mediterranean can be seen as a temperature residual in the boundary layer as well.

Acknowledgment

The World Data Centre A for Meteorology at the Goddard Space Flight Centre has kindly provided the ISCCP-C1 one data and ERBE data. J J Morcrette created monthly averages from those datasets.

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