DIAGNOSIS OF DIABATIC FORCING

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1. INTRODUCTION

The last fifteen years of operational forecasting have shown the importance of diabatic forcing for the quality of medium-range predictions. A typical example can be seen in the growing importance attributed to radiation for producing realistic forecasts in the range of a week or more. Particularly the geographically fixed prescription of clouds led to a misrepresentation of the cloud-radiation interaction, which limited the improvement of some near surface forecast parameters. Diagnostic cloud schemes that are linked to large-scale properties of humidity, vertical velocity, stability and model rainfall (*Slingo*, 1987) were used in a number of forecasting models because of their simplicity and relative success in representing the gross features of clouds. However, the increasing demand on forecast quality and particularly the quality of near-surface parameters cannot be met by a diagnostic cloud scheme. The decoupling of the cloud diagnosis and the hydrological cycle imposes limits on the correct simulation of clouds. A diagnostic study based on cloud data from the Atlantic Stratocumulus Transition Experiment (ASTEX) showed that most predictors, except relative humidity, used in the ECMWF parameterization of low-level clouds performed rather poorly (*Bretherton at al*, 1995), with the effect that the observed day-to-day variations or the diurnal cycle of low cloud cover could not be reproduced by the model.

A better representation of cloud related processes could be achieved by deriving clouds from large-scale budget equations of cloud water and cloud air (*Tiedtke*, 1993). Experimentation at ECMWF with this new prognostic cloud scheme showed, for example, a substantial improvement in the representation of the temperature at 2 metres (*Jacobs*, 1994).

The importance of parametrized sub-grid scale processes for the quality of medium-range forecasts requires increasing efforts to provide independent data for model verification. Only very few diabatic processes can be verified by using observational data directly. In this respect the global coverage of satellite radiance measurements has helped enormously to validate the radiation-schemes and, in particular, the cloud-radiation interaction. Most other diabatic processes can only be verified indirectly by performing some kind of budget calculations using observational data.

Here the question arises which data type would be most suitable for validation purposes. Field experiments provide, in general, a sufficient data density to investigate the performance of parametrization schemes under specific circumstances and for a suitable location. However, for a global validation the data coverage is not sufficiently dense, therefore large-scale analyses are used to estimate diabatic forcing from a residual of large-scale budget calculations. The convenience of having data on a regular grid covering the globe and a fairly good resolution in time has to be paid for by one important disadvantage. As large-scale analyses are normally the product of an observational increment added to a first guess that itself is a short-range model forecast, the analysis may be contaminated by model errors. A further model influence on the analyzed fields arises from the diabatic model tendencies that are used in the normal mode initialization. Therefore the problem for data sparse regions in particular is that the model employed in the data assimilation can introduce errors into the analysis from the same parametrized processes one wants to verify.

The advantage of using the data assimilation environment is that a high degree of consistency can be achieved when diabatic forcing derived from large-scale analyses is compared with model parametrizations. This can be realized by using the model itself to calculate the dynamical tendencies and the tendencies from the parametrization schemes. Employing this approach *Klinker and Sardeshmukh* (1992) have shown that large imbalances between dynamical and parametrized tendencies can indeed give an indication of problems in the parametrization scheme. The fact that a residual in the sum of the two tendencies was found in the average over a large number of initial forecast steps showed that useful information had been assimilated during the analysis that revealed problems in the way gravity-wave drag was parametrized initially at ECMWF.

2. BUDGET CALCULATIONS FROM LARGE SCALE ANALYSES

2.1 Analysis problems affecting budget calculations

During autumn 1993 and winter 1993/94 relatively large systematic temperature errors were found over tropical land areas. Too high temperatures in the boundary layer in the short-range forecast and a large underestimation of convective rainfall were consistent with the fact that the humidity in the analysis showed a large dry bias as measured against surface observations. A careful investigation of the analysis changes in the boundary layer showed that the use of low-level mass data produced a negative temperature increment. Without using the 2m dew point observations from SYNOP stations and keeping the relative humidity constant, the result was a predominantly negative humidity increment. The problem of an analysis drift in the humidity analysis was exposed by the new parametrization scheme of surface processes that allows a more realistic adjustment of soil moisture to observed anomalies (*Viterbo and Beljaars*, 1994), whereas the climate reservoir of soil water in the scheme operationally before August 1993 imposed a certain limit on a possible drift of soil humidity.

An analysis problem like insufficient low-level humidity raises the question as to what extent budget calculations of diabatic forcing are affected. As part of the Joint Diagnostics Project between the Department of Meteorology of the University of Reading and the United Kingdom Meteorological Office diabatic heating rates have been estimated from the residual of the thermodynamical equations based on the ECMWF analysis (*Hoskins et al*, 1989). Their calculations show a sensitivity of the derived diabatic forcing to model and analysis changes. In particular, the change of the radiation scheme and convection scheme in 1989 led to a noticeable enhancement of the estimated diabatic heating. It is therefore not surprising that an analysis error like the dry bias in autumn 1993 and winter 1993/94 had a detrimental effect on the inferred diabatic forcing. The large negative anomalies of the vertically integrated diabatic heating for winter 1993/93 (Fig 1) are consistent with the analysis being too dry over large parts of the tropical continents. A similar effect was noticed in the hydrological processes parametrized in the model. In particular the convective rainfall produced by the model was substantially lower over Central Africa than during previous winter seasons.

The long-term drift of soil moisture and low-level humidity in the analysis is an example of how weaknesses in the data assimilation system may be exposed by an improved model formulation. By deriving an analysis increment of low-level humidity and soil moisture from the 2m dew point information, a realistic low-level moisture analysis could be restored.

2.2 Model influence in data sparse regions

The geographical distribution of diabatic heating is an important ingredient of the Indian summer monsoon. The diagnosis of the diabatic heating helps to understand the mechanism of the monsoon flow. However, the Indian Ocean is an area of rather low data coverage. Additional problems arise from poor quality of height reports from radiosondes over the Indian subcontinent. Although the quality of cloud track winds in the Indian Ocean has been improved recently, the wind estimates are still straying too far from the background field to be accepted in the analysis.

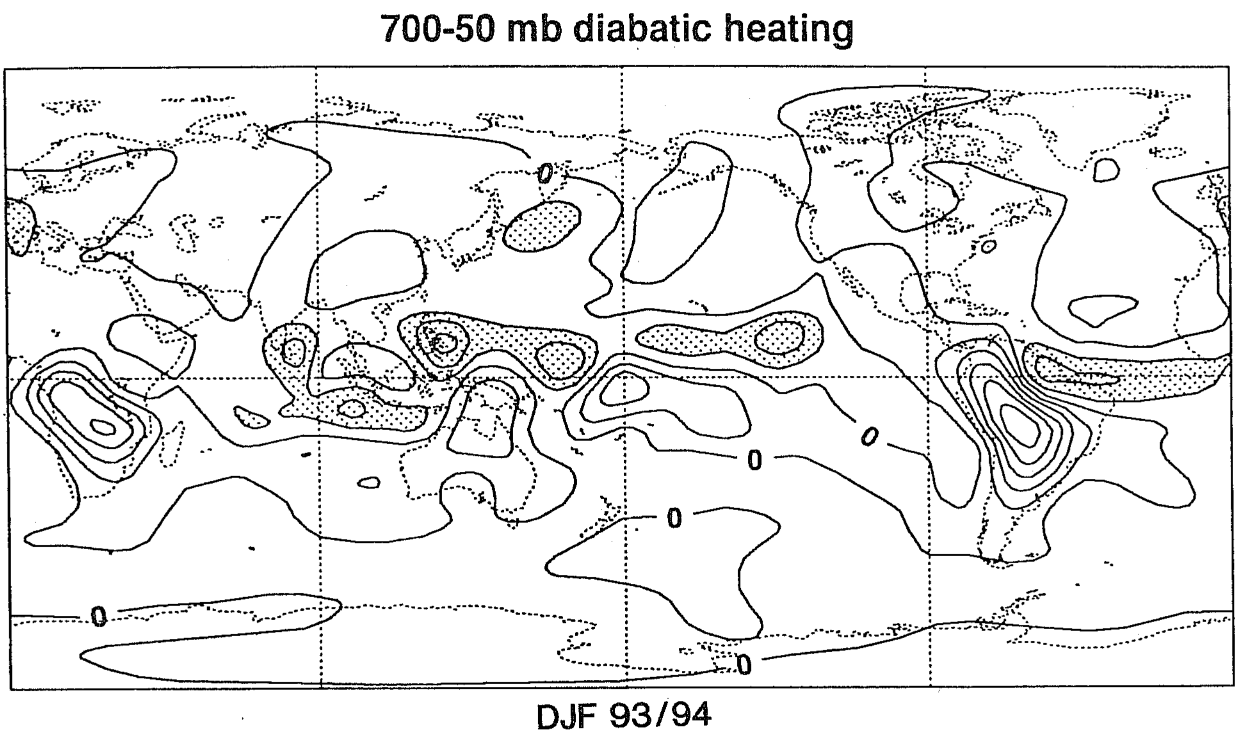

Fig 1 Anomaly of the vertically integrated diabatic heating (DJF 1993/94 - DJF 5 years). Calculations are performed in the Joint Diagnostics Project between the Department of Meteorology of the University of Reading and the United Kingdom Meteorological Office. Figure kindly provided by P Berrisford.

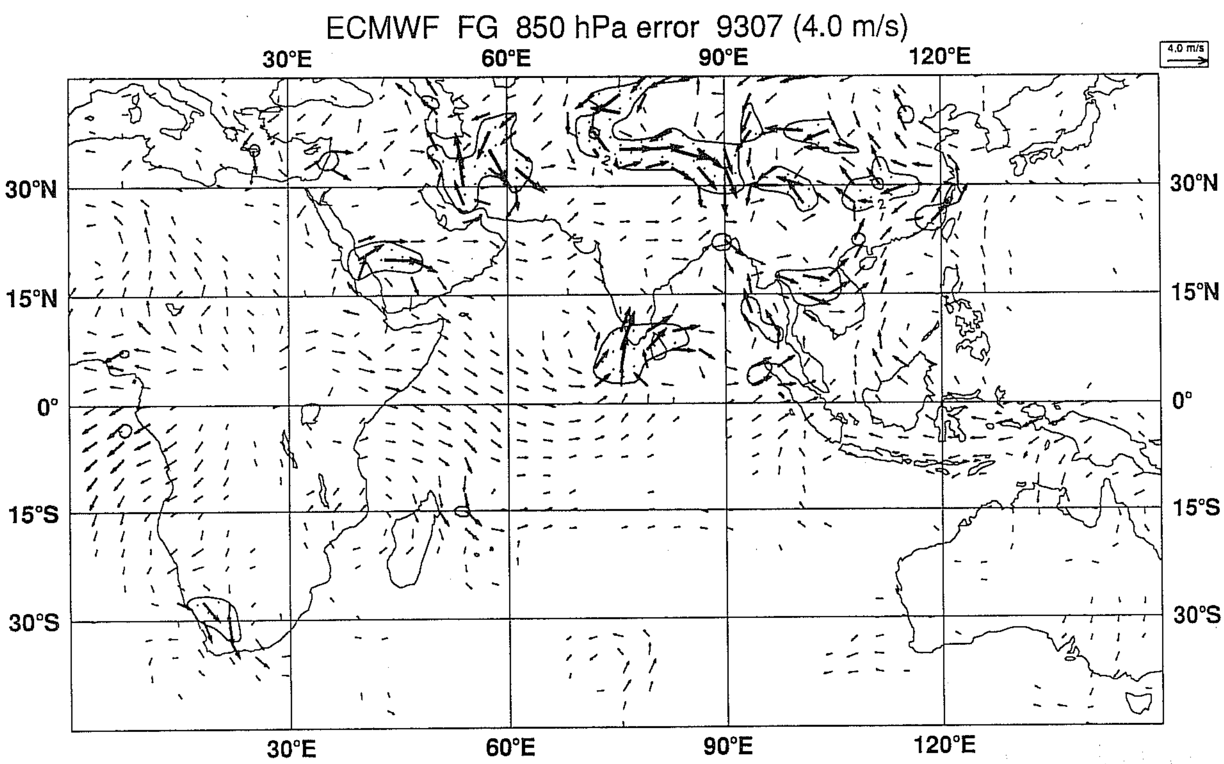

Fig 2 Analysis increment for the 850 hPa wind in July 1993. Unit: 4 m/s.

On the basis of a rather low amount of acceptable data, the analysis produces only small increments over the oceanic areas (Fig 2). Comparatively large increments are only found over southern parts of India and other tropical and subtropical land regions. The dominant influence of the model on the analyzed monsoon flow is further underlined by the fact that the seasonally averaged day-10 forecast is almost identical to the mean analysis.

The small impact of data on the analyzed monsoon flow reduces the value of the information one can deduce from the diagnosed diabatic heating. Under these conditions, there is an almost perfect balance between the diabatic heating calculated from the dynamical tendencies and the parametrized diabatic heating as shown in the east-west cross section for a latitude band from 10 to 20 degrees north (Fig 3). In order to assess the quality of the diabatic heating estimates, other direct measurements related to the diabatic processes like rainfall or outgoing long wave radiation are used.

Rain-gauge data is still the most valuable source of information for a continuous validation of operational rainfall forecasts. The station network over India and over South-East Asia is dense enough to show a clear sign of systematic model deficiencies (Fig 4). Over most land areas the model seems to over-predict precipitation, with a particularly large positive bias along the west coast of India where the model values represent an overestimate of around 15 mm per day. The positive bias in the rainfall is consistent with other indications that the vertical structure of the convective processes is not correct. The vertical profile of the diabatic heating (Fig 3) shows that the convective heating in the model has largest values along the west coast of India and is as deep as further downstream over the Bay of Bengal and South East Asia. A distribution of deep convection like this is not supported by OLR measurements (not shown). The lowest OLR values are found further to the east over the maritime continent.

3. MONITORING OF THE ECMWF MODEL

Analysis errors or insufficient data density available to the analysis impose a limit on using estimates of diabatic forcing for the validation of the model parametrization. However, experience has shown that the calculation of an initial model tendency residual as the sum of the adiabatic and diabatic tendencies averaged over a month provides sufficient information on possible model problems (*Klinker and Sardeshmukh*, 1992). Running the model in a diagnostic mode that allows all dynamical tendencies and the tendencies from the various parametrization schemes to be saved, increases the memory requirements to such an extent that only a lower resolution of T106 compared to the operational T213 can be used. At ECMWF normally one winter and one summer month are selected for a detailed diagnostic investigation.

The zonal mean thermodynamic budget for July 1974 is shown in Fig 5. Instead of using true initial tendencies the diagnosis had to be based on model tendencies after the first hour when, for technical reasons with the model version in operational use at that time, the radiation scheme starts to take convective clouds into account. All tendencies are therefore based on model tendencies between hour one and hour two.

Figure 5 shows the zonal mean of the dynamical tendencies with the sign reversed (a), the sum of all tendencies for the parametrized heating (b) and the total tendency (c) as a difference between (b) and (a). As a comparison to the budget residual, the monthly mean day-1 forecast errors are shown in (d). The parametrized tendencies are then further subdivided into the contributions from different processes: radiation (e), cumulus convection (f), large scale condensation (g) and vertical diffusion (h).

The imbalance between the dynamical tendencies and tendencies from the parametrization scheme is generally fairly small. During the last few years a reduction of the budget residual indicates that the balance

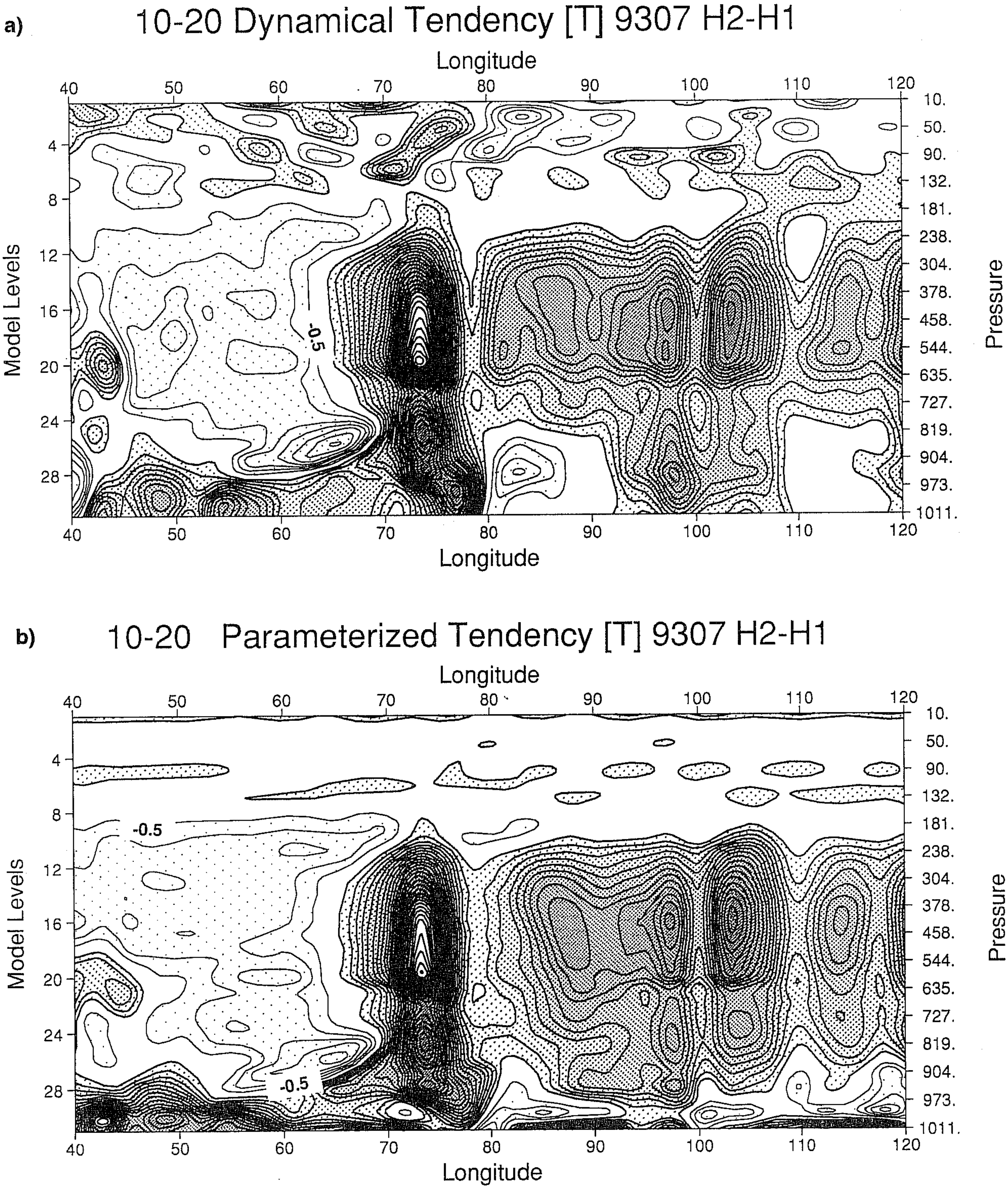

Fig 3 Vertical cross section of dynamical temperature tendencies with the sign reversed (a) and diabatic heating (b) for July 1993 as a north-south average from 10 to 20 degrees north. Tendencies are calculated as differences from two and one hour steps of short range forecasts run from six-hourly analysis of one month. Unit: K/day.

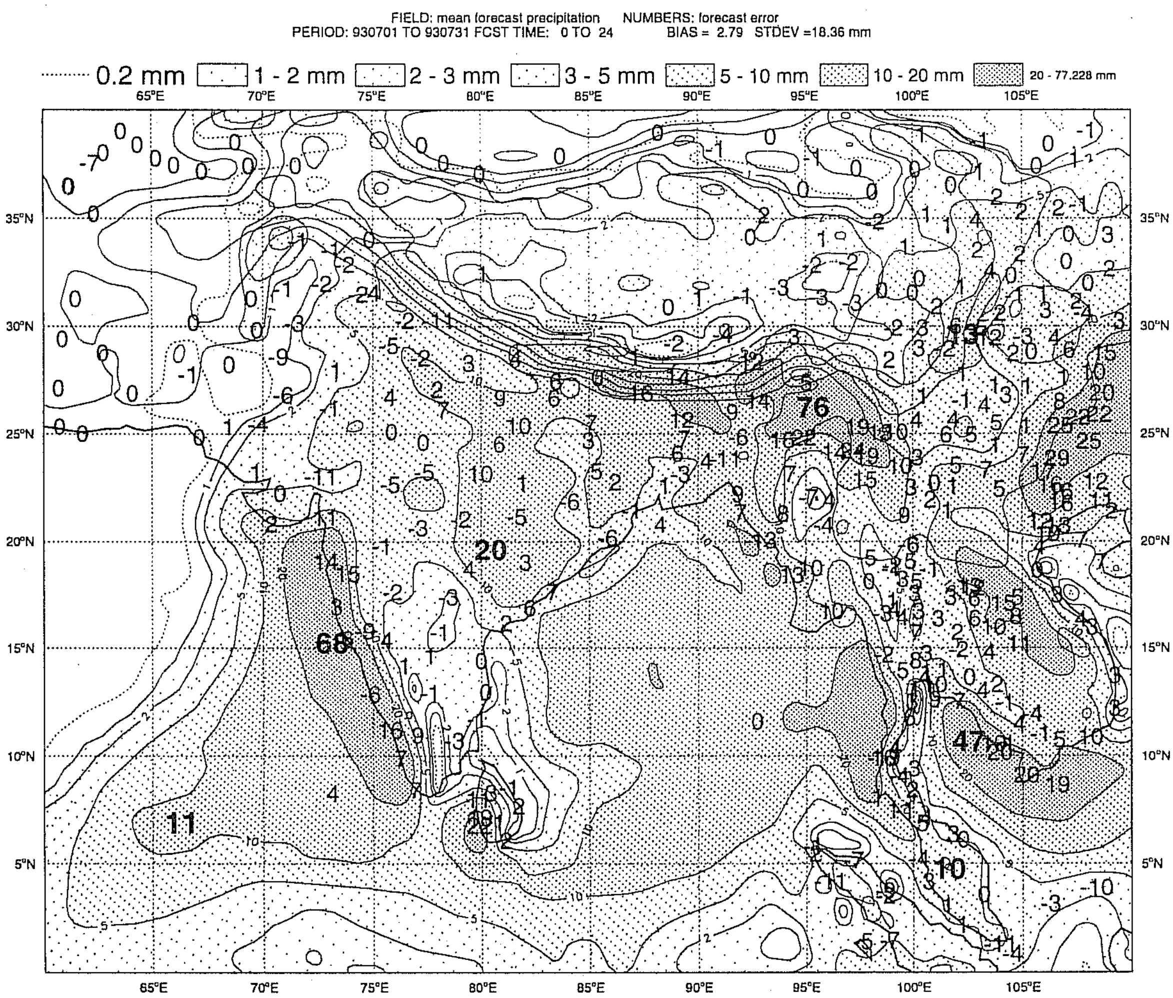

Fig 4 Mean day-1 forecast precipitation (contours) and precipitation differences between forecast and station observation (numbers) for July 1993.

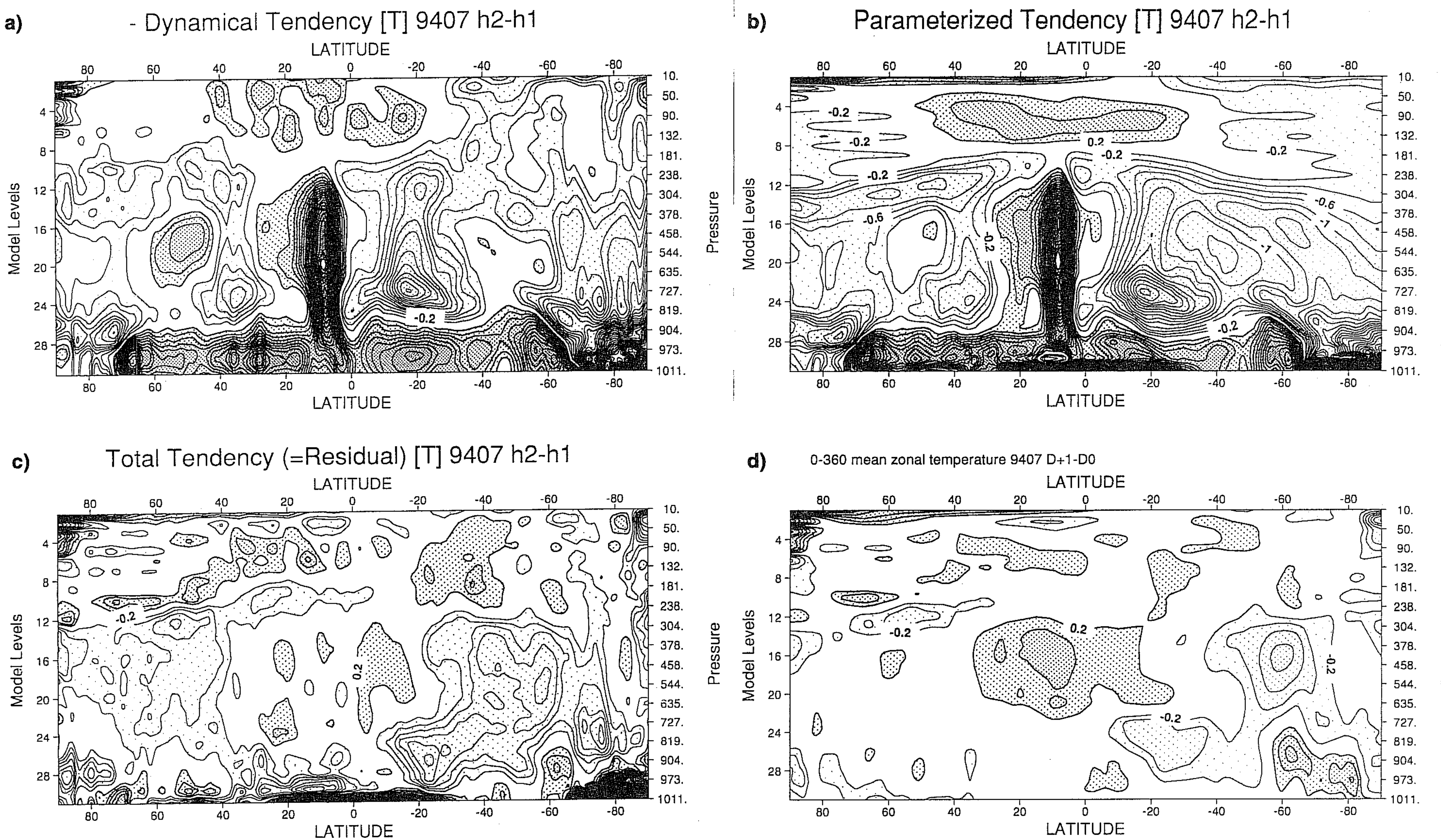

Fig 5 Cross section of the zonal mean of the dynamical tendencies with the sign reversed (a), the sum of all tendencies for the parameterized heating (b) and the total tendency (c) as a difference between (b) and (a). The monthly mean day-1 forecast errors of temperature (d). The parametrized temperature tendencies from radiation (e), cumulus convection (f), large scale condensation (g), and vertical diffusion (h). Monthly mean values for July 1994. Unit: K/day.

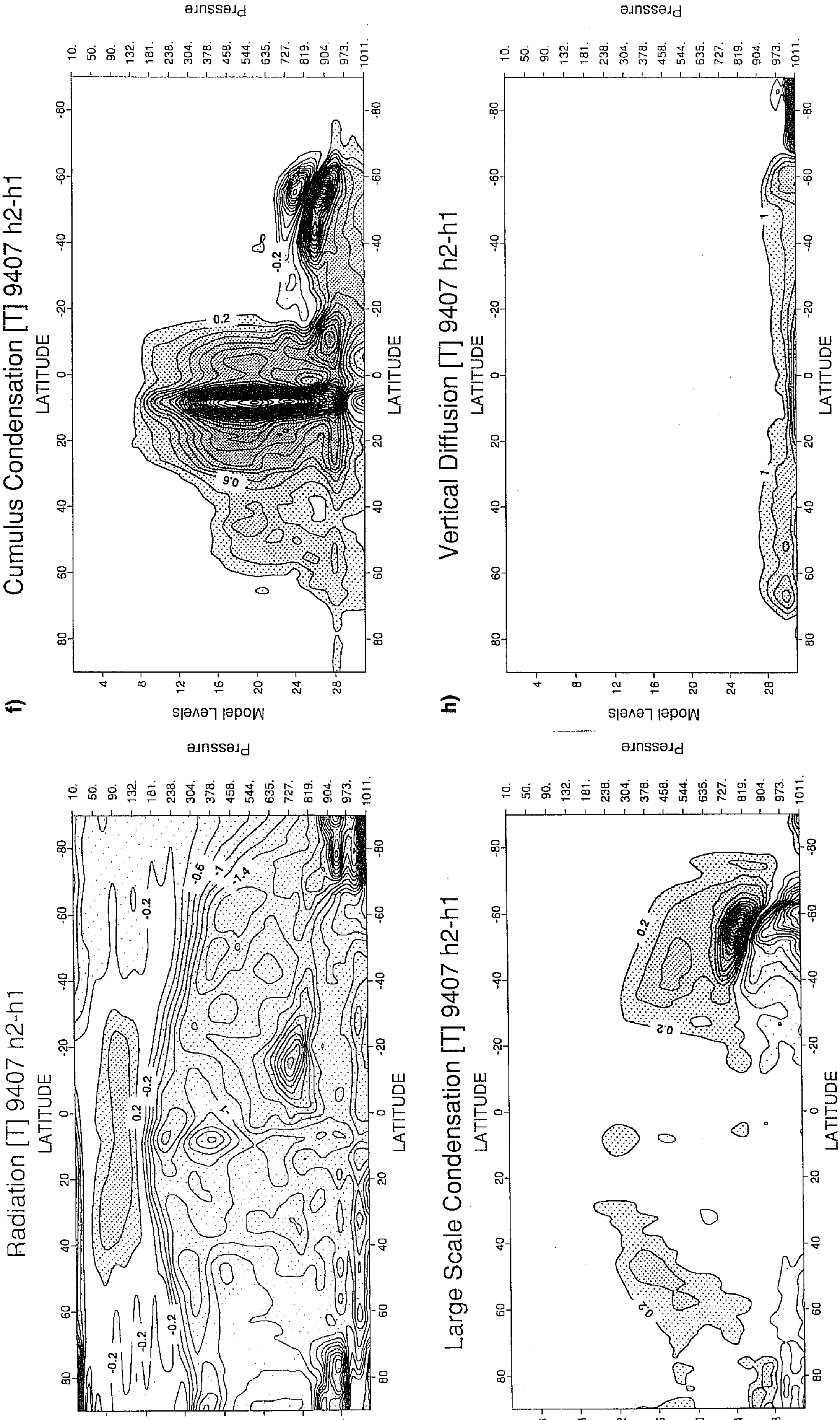

Fig. 5 continued

between the diabatic and adiabatic tendencies has been improved. As in previous years, quite a number of features in the residual pattern develop into short-range forecast errors of a similar structure (Fig 5d). This type of forecast error development gives us confidence that the residual from the first two hours of the forecast is representative of the systematic error at least in the short range.

For July 1994, the two major areas of a negative budget residual are found in the latitudes of extra-tropical storm tracks. The imbalance points to a problem mainly confined to the short-range forecast when the diabatic heating from the large-scale rainfall is underestimated. This insufficient diabatic heating from large scale condensation processes is linked to the reduction of relative humidity in the analysis. Particularly in areas where the model reaches the threshold of 100%, which represents the lower limit for condensation to occur in the model, observational humidity supports only a significantly lower value.

A more persistent feature is the cooling in the subtropical boundary layer. Based on diagnosing the thermodynamic budget for June 1992 in the subtropical Atlantic, *Bretherton et al* (1995) suggested a strong link between the systematic model errors and maximum radiative cooling in the vicinity of the inversion clouds. As this occurred even in the presence of a dry bias in the boundary layer it is not surprising that the boundary layer cooling increased even further with a model change in early 1994 that enhanced the shallow convection and increased the moisture especially in the top parts of the boundary layer.

The cloud-radiation interaction gives rise to a negative budget residual at other places as well. At high latitudes a negative budget residual close to model level 28 is consistent with the model definition that this is the lowest model level where cloud existence is allowed. A criterion like this was necessary to prevent unrealistic occurrence of clouds close to the ground that led to spurious cooling of the near surface layer. It is hoped that the prognostic cloud scheme leads to a more realistic distribution of clouds in space and time and singular cloud layers are not the result of parametrization constraints but rather a reflection of observed cloud structures.

Negative budget residuals associated with cloud-radiation interaction close to the tropopause have been reduced substantially in the last few years. The dipole structure of the small residual around the tropopause suggests some contributions from unbalanced dynamical tendencies.

4. INTERACTION OF PHYSICS AND DYNAMICS

The significance of diabatic forcing for the development of meteorologically relevant systems is often difficult to estimate from the single components of the thermodynamical and mechanical processes. The framework of potential vorticity offers the possibility to describe the evolution of such systems with a single equation

$$\frac{D\,PV}{Dt}=\frac{1}{\rho}\zeta.\nabla\dot{\theta}+\frac{1}{\rho}\mathbf{K}.\nabla\theta \quad (1)$$

From numerical experimentation it is well known that the latent heat release plays an important part in the development of mid-latitude cyclones. *Hoskins et al* (1985) have shown that the concept of potential vorticity is particularly useful for diagnosing the role of diabatic process in the development of PV anomalies. From the budget equation for potential vorticity follows that the gradient of diabatic heating $\nabla\dot{\theta}$ in the free atmosphere and the frictional force-curl $\mathbf{K}$ in the boundary layer are likely to produce large local changes to the potential vorticity. For the interpretation of the diabatic terms of (1) it is important to note that diabatic processes are not able to create PV locally. The equation of the mass integrated PV over a

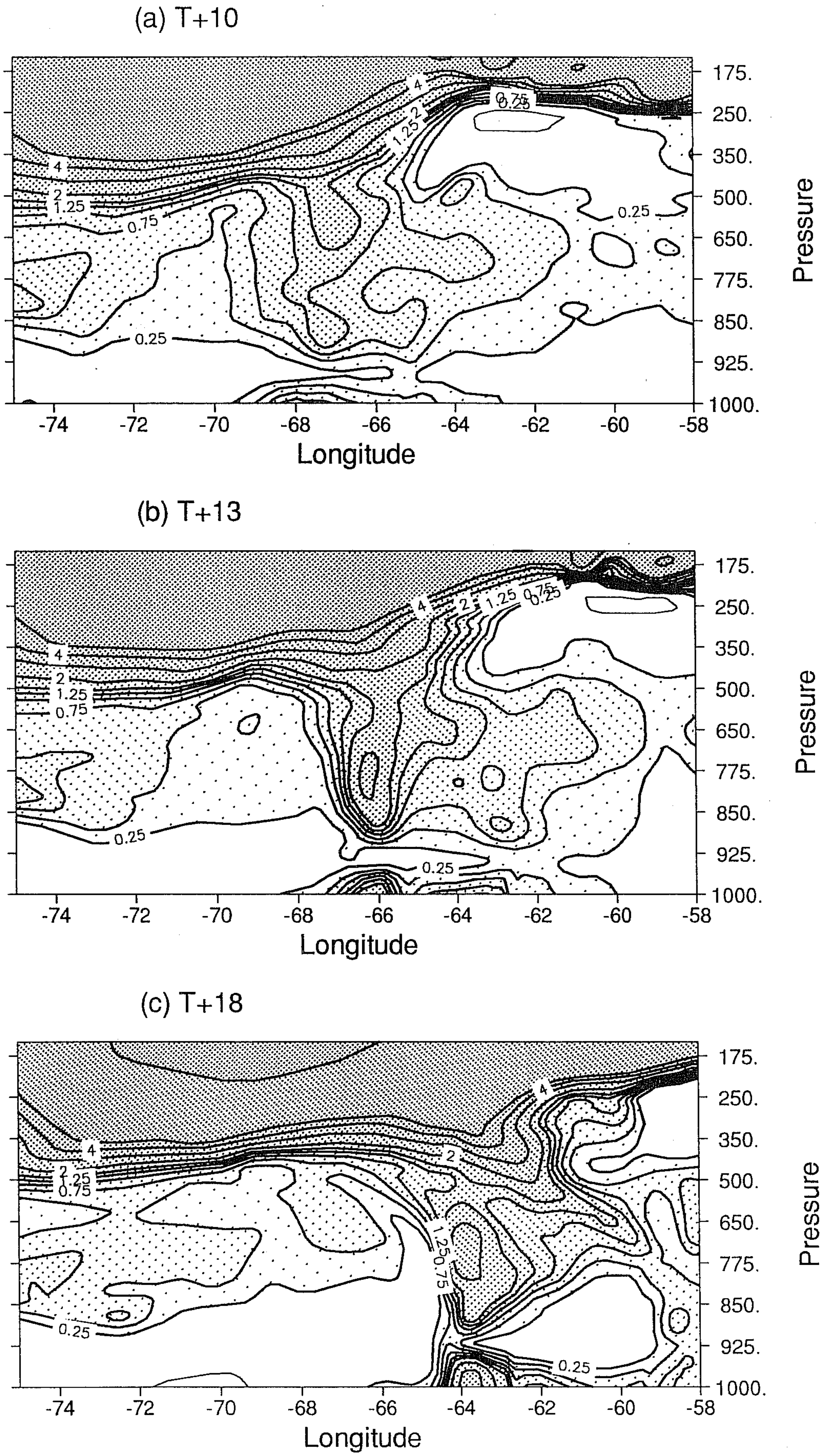

Fig 6 Vertical west-east cross section of PV (average over 35-40N). Contours: -0.25, 0.25, 0.5, 0.75, 1.0, 1.25, 1.5, 1, 2, 3, 4 PV units.

material volume shows that diabatic processes act to redistribute the interior PV, the integrated PV can only be changed if there are non-zero values along the volume boundary.

Dell'Osso and Klinker (1994) showed the importance of diabatic forcing for a rapidly developing cyclone using the limited area model. The development of PV in this so called ERICA IOP-4 cyclone seems to be influenced by intensive diabatic heating in the lower troposphere.

The vertical structure of the development is shown in a fairly broad west-east cross section representing a latitudinal average of 5 degrees which includes most parts of the PV anomaly associated with the cyclone (Fig 6). At T+10 a tongue of high PV anomaly extends from the upper troposphere into the lower troposphere. A surface anomaly is separated from the upper level anomaly by minimum values of PV. Between T+10 and T+13 hours PV increases in the column of the cyclone centre below 400 hPa. Clearly the largest change occurs around 800 hPa where the PV increases from 1 to 2 PV-units in three hours.

At this stage the cyclone development is accompanied by intensive condensation processes (Fig 7). The limited area model run with 20km resolution produces large amounts of rainfall from the resolved large scale processes and from the cumulus convection parametrization. Maximum large-scale condensational heating rates of up to 2 degrees per hour are seen in the centre of the cyclone. In the warm front area to the east of the cyclone centre the precipitation rate is only slightly weaker. However, for the effect of the condensational heating on the PV development (Fig 8), the location of large gradients relative to the PV anomaly is most important. According to the first term at the rhs of the PV-equation (1), negative PV-tendencies are found above and positive ones below the maximum condensational heating rate, which is located at 650 hPa (Fig 7a). These tendencies indicate a flux of PV from the upper troposphere to the lower troposphere. Further areas of large positive PV tendencies are seen along the sharp gradient between the levels of condensation and evaporation of falling rain.

The condensational heating by the parametrized cumulus convection (Fig 7b) has a different vertical structure compared to large scale condensation. It is also noticeable that areas of strong evaporation of rainfall (non-shaded negative values) shown in Fig 7a coincide with areas of condensational heating by cumulus convection. Therefore the effect of the cumulus convection on the PV development (Fig 8b) is partly compensated by the effects by large-scale condensation. However, the vertical structure and the location of maximum condensational heating rates of large-scale processes produce, in general, a larger contribution to the PV development in the lower troposphere compared to the tendency from the cumulus condensation.

A generally negative contribution of PV development at low levels arises from vertical diffusion of temperature in the boundary layer and from the exchange of heat with the surface. The boundary layer contribution of negative PV-tendencies is large enough to offset the large positive tendencies from the condensational processes, as can be seen from the sum of all diabatic terms in the PV budget equation (Fig 8c, rhs (1)). The net effect of diabatic forcing shows a clear sign of downward PV flux from around 450 hPa to the lower troposphere. The most intense redistribution of PV takes place in the centre of the existing PV anomaly, but also the frontal PV east of the cyclone centre increases by the diabatic processes.

The diagnosis of the potential vorticity budget reveals the importance of condensation processes for the rapid cyclogenesis. Diabatic heating around 600 hPa contributes to a flux of PV from the upper to the lower troposphere. Further experimentation and PV-diagnostics showed that evaporation of rain in the sub-cloud layer leads to a further intensification of the cyclone consistent with the suggestions of *Clough and Franks*

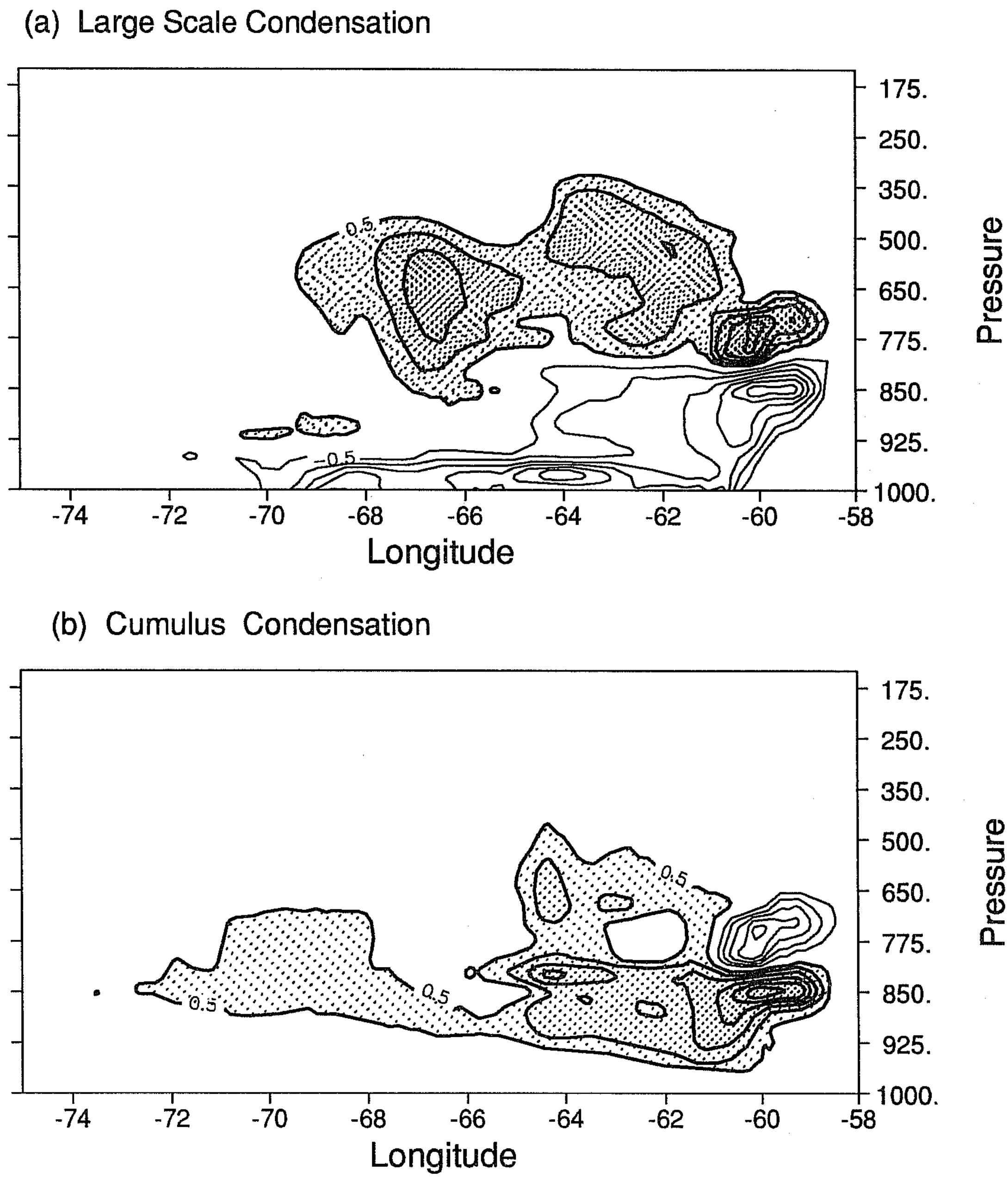

Fig 7 Vertical west-east cross section of diabatic heating by large scale condensation (a) and cumulus condensation (b). Latitudinal average from 35-40N. $\Delta t = t_{11} - t_{10}$. Contour interval: 0.5 K/hour, positive values are shaded.

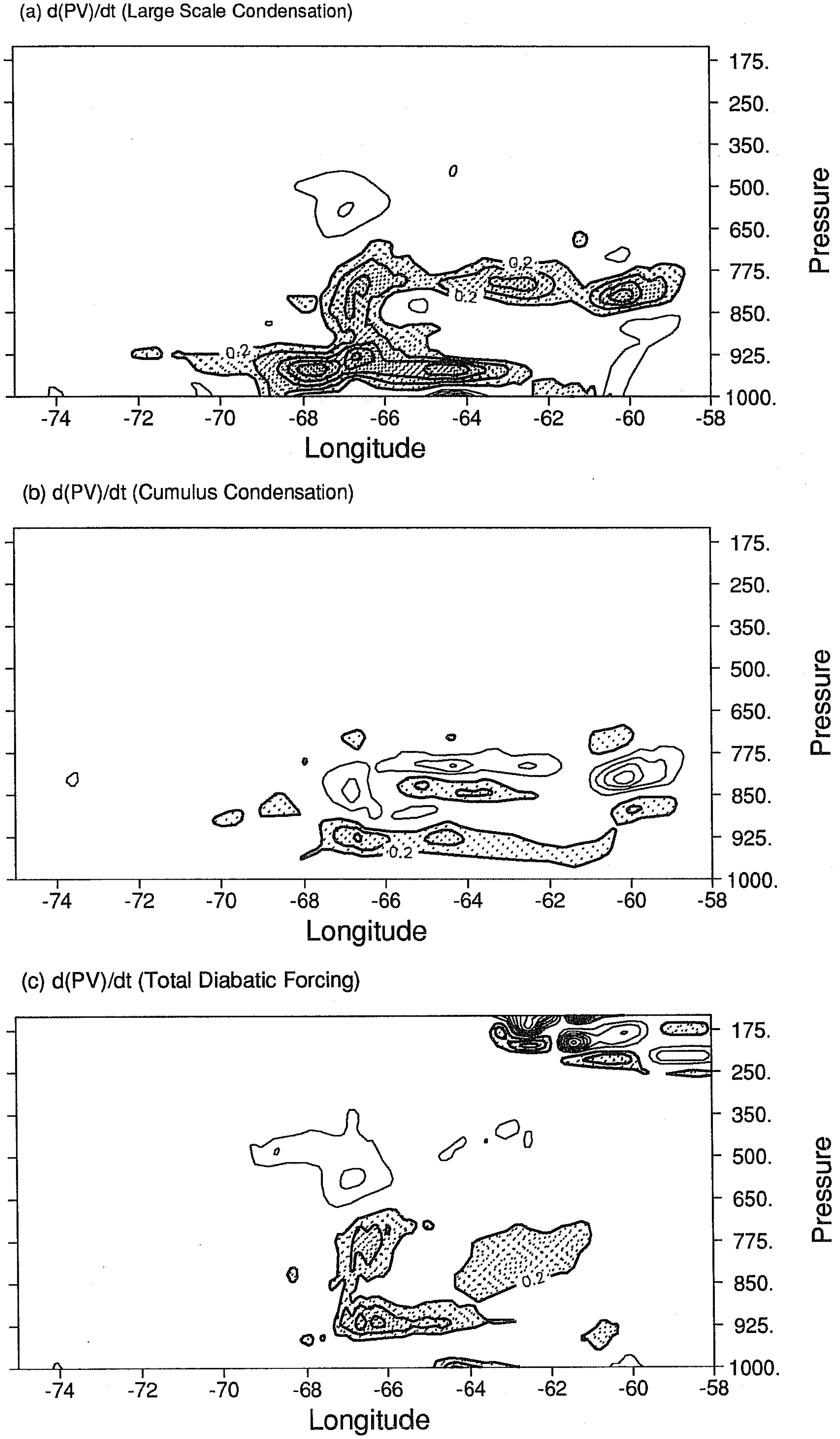

Fig 8 Vertical east-west cross section of diabatic PV-tendencies. (a) from large scale condensation, (b) from cumulus convection, (c) total forcing (rhs of (1)). $\Delta t=t_{11}-t_{10}$. Contour interval: 0.2 PV units/hour.

(1991) that evaporation of precipitation might be partly responsible for the frontogenetic behaviour of rapidly deepening cyclones.

5. SUMMARY

The diagnosis of diabatic processes has an important influence on the development of parametrization schemes in numerical models. As field experiments deliver high quality data for specific locations and for a limited period only, global estimates of diabatic forcing are also calculated as a residual from large-scale analyses. In a data assimilation environment, where the model can be used to produce dynamical tendencies and tendencies from parametrization schemes in a most consistent way, this approach has the potential of delivering a continuous validation of parametrization. By choosing this approach of model validation, one has to take into account that in the way data assimilation uses the short-range forecast as a first guess and the model is again used for initialization, the analysis may be strongly influenced by model errors arising from those parametrization schemes one wants to verify. The quality of the diabatic forcing will therefore strongly depend on the amount of data used in the analysis. Diabatic forcing in data sparse regions is unlikely to depart from the model values. A similar problem arises when the model evaluation based on large-scale budget residuals is done in a system using four-dimensional data assimilation products. As the resulting analysis will be a point on the model trajectory, dynamical tendencies that are used (with a correction of observed tendencies) to derive the diabatic forcing will be almost identical to the model's diabatic forcing.

For an evaluation of the effect of diabatic forcing on active systems like mid-latitude cyclone development the framework of potential vorticity is very useful. The equation of the mass integrated PV over a material volume shows how diabatic processes act to redistribute the interior PV thereby influencing cyclone development.

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