SPECIFICATION OF DIABATIC HEATING IN THE INITIALIZATION OF NUMERICAL WEATHER PREDICTION MODELS

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1. INTRODUCTION

Most analysis systems have difficulties in representing basic features in the tropical divergent circulation for a number of reasons. Firstly the data base is inadequate, particularly for the wind and moisture fields. Secondly the lack of high quality mass observations leads to aliasing between large scale Rossby and Kelvin modes which are known to be important in the tropics. Furthermore, tropical analysis schemes are unsatisfactory because of both formulation deficiencies and the performance of forecast models which provide the first guess for the analyses. For example, a number of analysis systems have a mid-latitude bias which is imposed through the use of assumptions such as non-divergence or geostrophy in analysis increments. While these assumptions are reasonably satisfactory in the mid-latitudes they are clearly not so in the tropics. Daley (1985) has proposed the use of divergent structure functions as a means of overcoming this problem. Recently Daley's formulation has been implemented in the ECMWF analysis scheme and preliminary results indicate a substantial improvement in the divergent analysis increments (Unden, 1988). Inadequate parametrization of physical processes, particularly cumulus convection leads to large systematic errors in model forecasts in the tropics. Although progress has been made in recent years a number of aspects of cumulus parametrization such as momentum transport and the interaction with the boundary layer flow are not well understood. Apart from causing forecast errors, these deficiencies in parametrization lead to analysis errors in the tropics.

Diabatic processes play a strong role in the tropical circulation. This is evident from satellite imagery, for example, which indicates regions of intense convective activity in various regions in the tropics. Fig. 1

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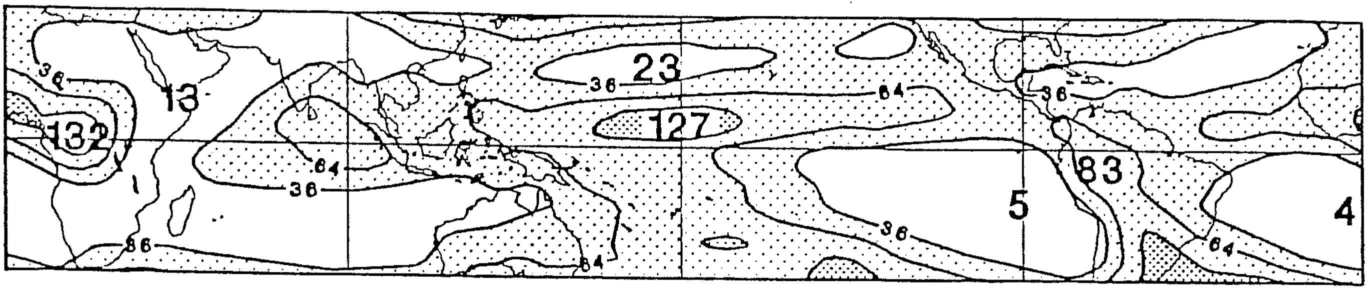
(provided by P. Sardesmukh) which shows the variance in 7 year outgoing longwave radiation (OLR) data in the 2 to 6 day band indicates strong convective activity in the central/western Pacific regions which incidentally are regions of very poor data coverage. Current analysis procedures are unable to include information about diabatic heating and thus the analysed divergence field may not be consistent with the diabatic heating. Although diabatic normal mode initialization (NMI) as used for example at ECMWF, attempts to include diabatic heating information, there are a number of problems associated with the specification of the heating. In a recent study Hollingsworth et al. (1988) have examined the tropical wind analysis produced by the assimilation of the Final FGGE II-b dataset. They found substantial errors in the 6-hour forecast of the mean tropical divergence field and in the intensity of the Pacific Trade winds. The large scale wind errors in the background field are largely corrected by the analysis scheme. However, the initialization step undoes about half of the effect of the analysis on the mean large scale wind fields. This is mainly due to the fact that the convective forcing used in the diabatic initialization is too weak. Another undesirable effect of improper specification of diabatic heating information is the well known spin-up problem in numerical models.

This paper describes procedures which makes use of OLR data to provide indirect information about diabatic heating and to initialize moisture. The use of OLR data in the analysis of the divergence field has been proposed by Julian (1984) and Krishnamurti and Low-Nam (1986). Julian, for example has proposed an algorithm which transforms satellite observed OLR data directly to a velocity potential field. In the procedure proposed here, heating rates deduced from the OLR data are used in diabatic NMI to derive an initialized divergence field. The procedure also modifies the moisture field so that the heating rates in the early stages of the model integration are consistent with those used during initialization. Thus it provides a means of combining the analysis of divergent wind field and initialization to produce an initial state which is well balanced and consistent with the regions of heating.

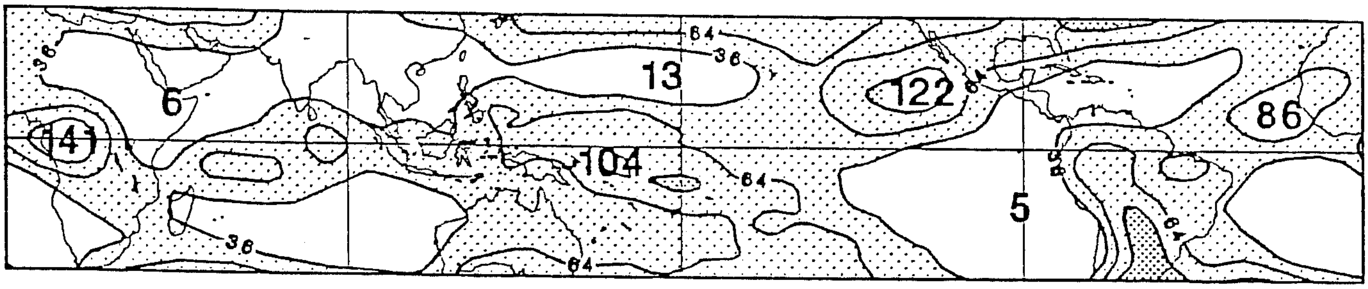
2. SOME FEATURES OF DIABATIC HEATING

Nonlinear NMI has proved to be extremely effective in controlling spurious gravity wave oscillations which occur in primitive equation models in the absence of an appropriate initial balance between the mass and wind fields.

ALL SEASONS



DECEMBER - FEBRUARY



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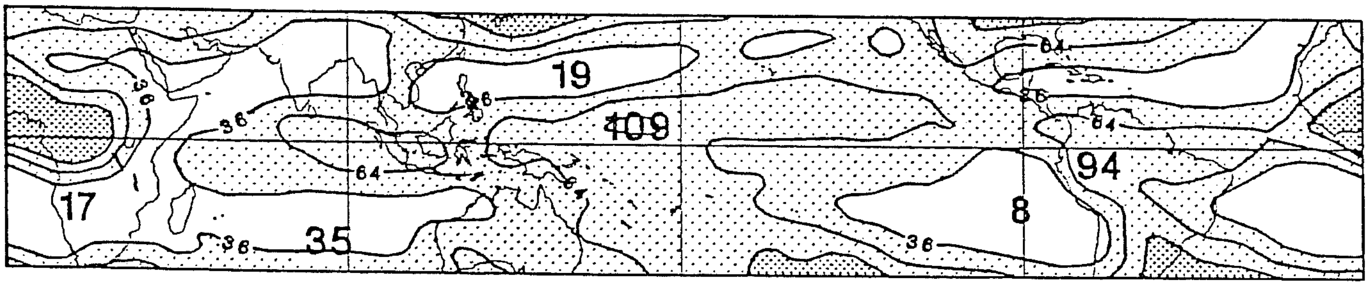

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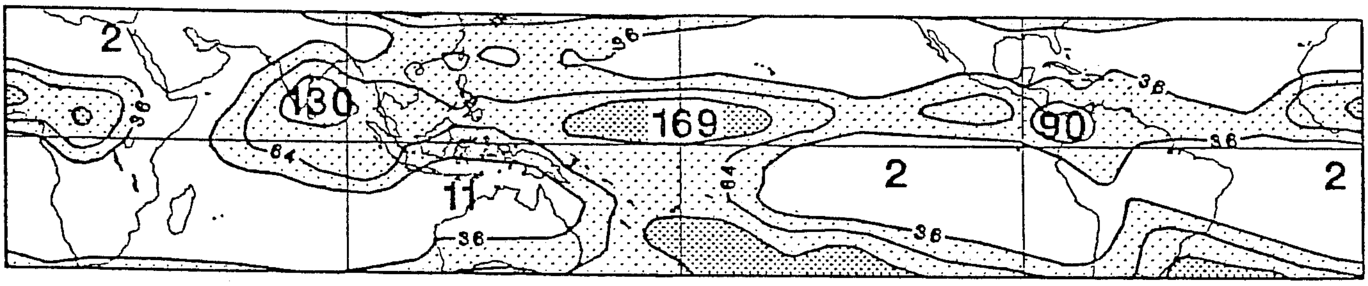

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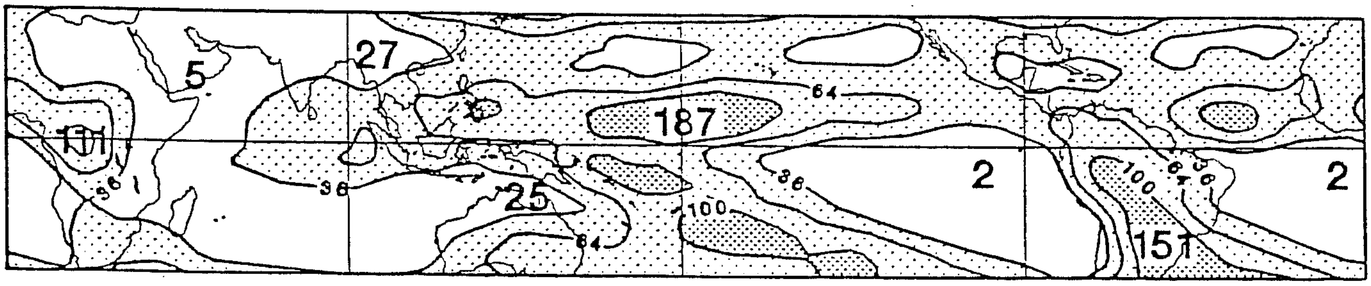


Fig. 1 OLR variance in the 2-6 day band using 7 years data. Values between 36 and 100 watts^2 m^{-4} are shaded lightly with enhanced shading for higher values. Contours shown are 36, 64, 100, 225, 400 and 625 watts^2 m^{-4}.

However, the use of adiabatic NMI leads to a drastic depletion of the tropical divergent circulation. One of the procedures to overcome this problem was proposed by Wergen (1982) in which a constant diabatic heating is used during initialization. Diabatic NMI as used at ECMWF involves the following steps:

- The model is integrated for two hours from uninitialized fields, and diabatic terms are accumulated;
- Time averages of diabatic terms over the two hour period are derived;
- The resulting fields are filtered such that only periods greater than 11 hours in the diabatic terms are retained. Furthermore a spatial filter is also applied such that the first 20 zonal wave numbers and 10 meridional wave numbers are retained. The time filter constitutes a strong damping on the diabatic terms;
- The filtered fields are then used as constant forcing during the iterative initialization procedure.

Puri (1987) studied various features of diabatic NMI by using specified analytic heating rates with different vertical structures. He found that diabatic NMI is able to achieve a well balanced initial state in the regions of heating provided the relevant vertical modes are initialized. The importance of initializing the higher vertical modes becomes more evident when shallower heating profiles are used. The persistence of balance achieved by NMI during the early stages of the model integrations is strongly dependent on the compatibility between the specified heating during initialization and the heating during model integration. Puri suggested that one possible way of retaining the compatibility in the heating rates would be to initialize the moisture field by adjusting its value until the heating rates implied by the convective parametrization in the model are similar to those used during NMI.

There are a number of problems associated with diabatic NMI as used at ECMWF. Firstly the time filtering is excessive. This is evident in Fig. 2 which shows the heating rates at a model level close to 500 hPa before and after the application of the filter. Relaxing the time filter to 5 hours leads to stronger heating rates. The latter filter also has the desirable feature

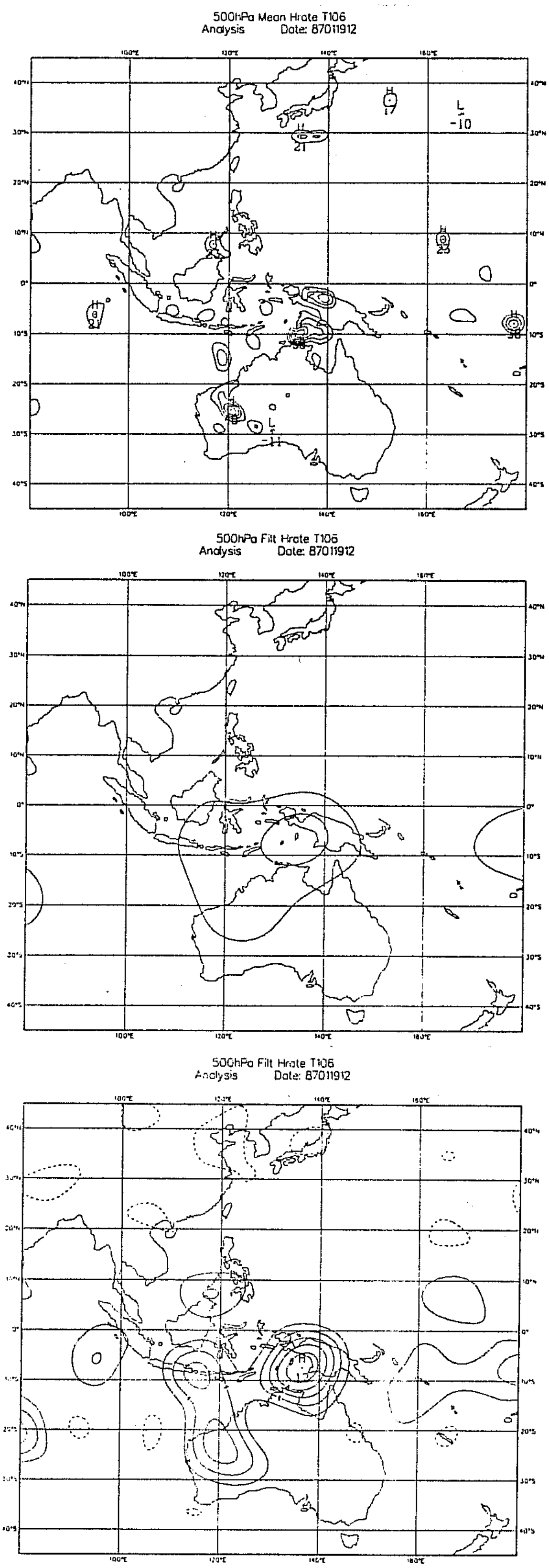


Fig. 2 Unfiltered heating rates at model level close to 500 hPa (top), after operational filter (middle) and after using time filter of 5 hours (bottom). Contour intervals for the unfiltered and filtered heating rates are 10° day^{-1} and 2° day^{-1} respectively.

that it retains most of the structure of the unfiltered heating rates. As was indicated earlier, the study of Hollingsworth et al. (1988) showed that the initialization step undoes about half of the effect of the analysis on the large scale wind field. Relaxing the time filter, might alleviate this problem by increasing the intensity of heating rates used during initialization.

The commonly used procedure of applying model generated heating rates during diabatic NMI can lead to problems arising from deficiencies in the parametrization of convective processes and analyses of divergence and moisture fields; thus for example the heating rates might be too weak or convective processes might occur at incorrect locations. Thus the specification of convective heating rates remains a major problem in diabatic NMI. Although no procedure exists as yet of directly measuring heating rates, OLR data provides indirect and approximate information and the remainder of the paper will discuss this application.

3. USE OF OLR DATA

Puri (1987) proposed a procedure in which the OLR data was used to identify regions of deep convection. Heating rates were then specified over these regions and used in diabatic NMI. However, the specification of the intensity and vertical profile of the heating rates in this study was somewhat arbitrary and still remains an outstanding problem. In this paper, an attempt is made to extend the idea of Puri (1987) by proposing more objective procedures for specifying convective heating rates.

a. Derivation of precipitation rates from OLR data

The OLR data used in this study was obtained from the NOAA-9 satellite and was available on a $2\frac{1}{2}^\circ \times 2\frac{1}{2}^\circ$ latitude-longitudes grid. Arkin (Private communication) has derived regression between OLR fluxes and precipitation rates in the tropics from monthly mean data on the $2\frac{1}{2}^\circ \times 2\frac{1}{2}^\circ$ grid. The same formula was used here to provide estimates of the daily rainfall as a means of illustrating the procedure. The following relationship was used:

$$\dot{R} = \begin{cases} 0 & \text{if OLR flux} > 280 \text{ watts m}^{-2} \\ -0.175*(\text{OLR}-280.) & \text{otherwise,} \end{cases} \qquad (1)$$

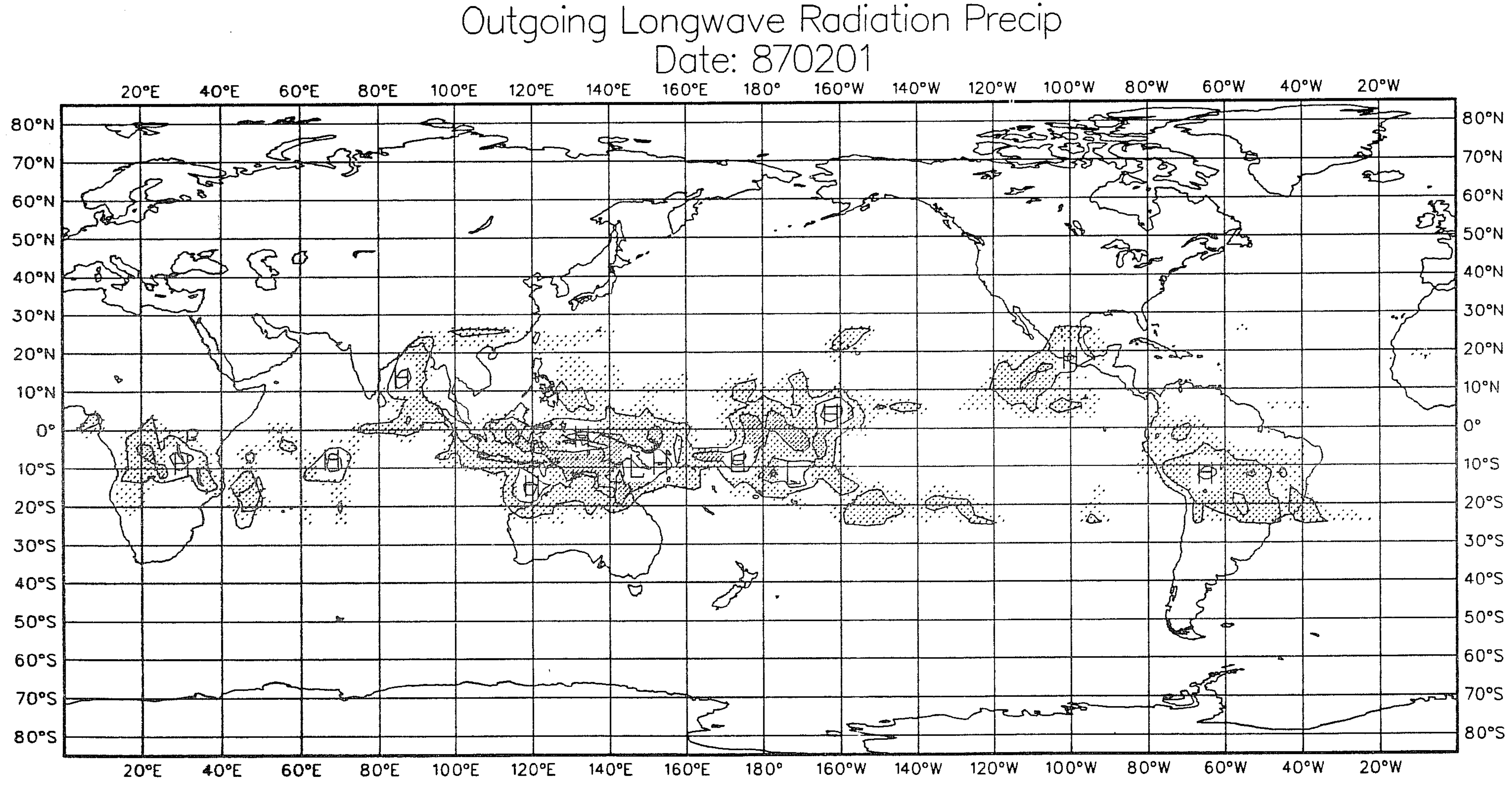


Fig. 3 Rainfall rate derived from OLR data. Units are mm day^{-1} and contour interval is 10 mm day^{-1}. Values above 5 mm day^{-1} are shaded with enhanced shading for higher values.

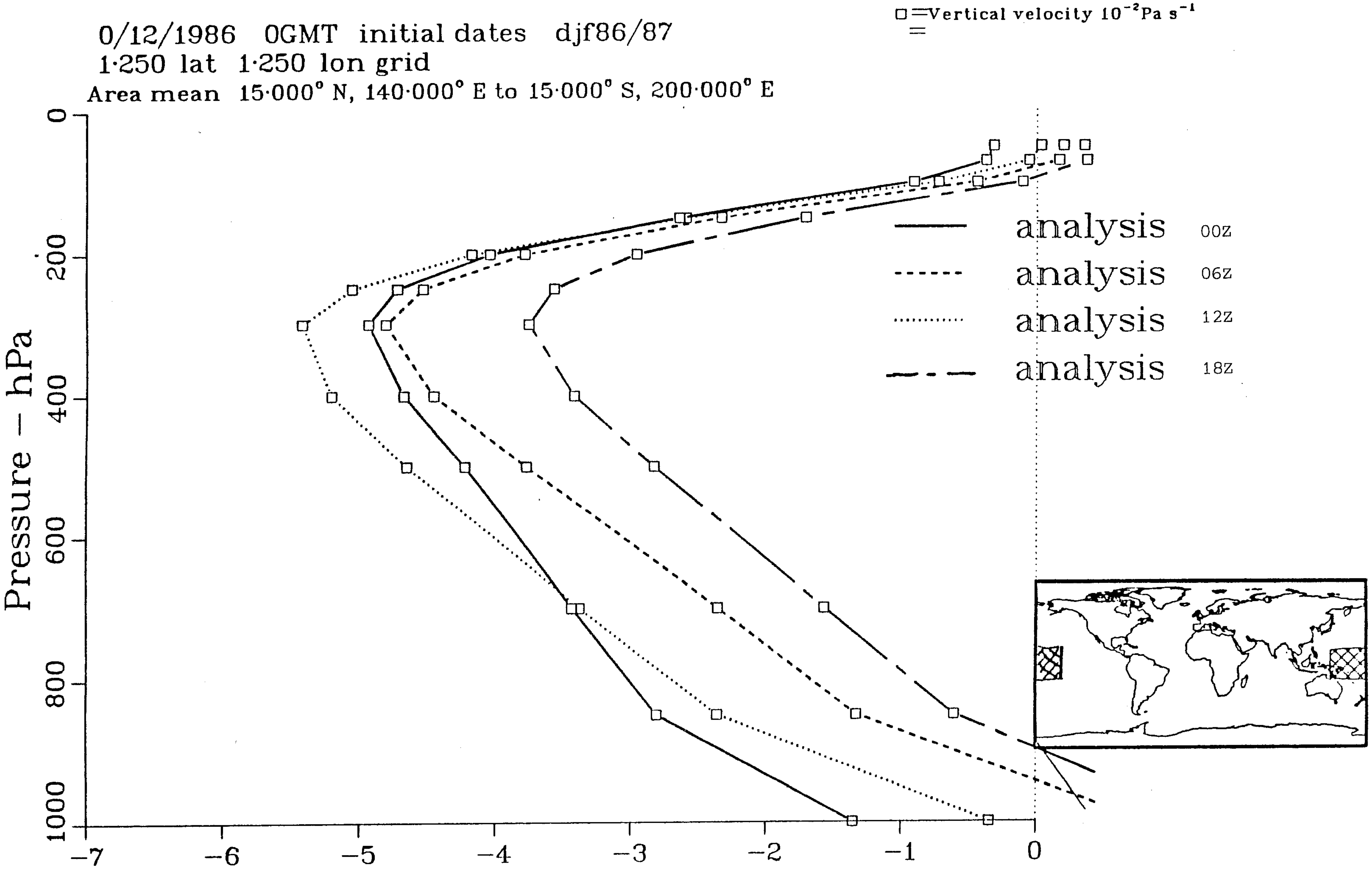


Fig. 4 Mean vertical velocity profiles for DJF 86/87 based on 00Z, 06Z, 12Z and 18Z analyses.

where $\dot{R}$ denotes the rainfall rate in mm day^{-1}. The rainfall rate is essentially a measure of the vertically integrated heating rate at the particular location, ie

$$\int_{p_B}^{p_T} C_p \frac{\partial T}{\partial t} \, dp = L\dot{R} \tag{2}$$

where p_T and p_B indicate the pressures at the top and bottom of the column, C_p is the specific heat and L is the latent heat of evaporation. Fig. 3 is an example of the rainfall rate recovered from OLR fluxes using relation 1. Note that in this study relation 1 was only used in the region 25°N to 25°S as the relation between OLR fluxes and convective precipitation is only valid in the tropics. The NOAA-9 satellite provides OLR fluxes at each location twice per day. This could be extended to four times per day if both NOAA-9 and NOAA-10 satellites were used.

b. Intensity and vertical profile of the heating rates

Two methods for determining the convective heating rates from the derived rainfall rate will be proposed. In the first method the vertical profile of the heating is specified and the intensity of the heating is then simply determined from equation (2). Thus if we express $\frac{\partial T}{\partial t}$ as

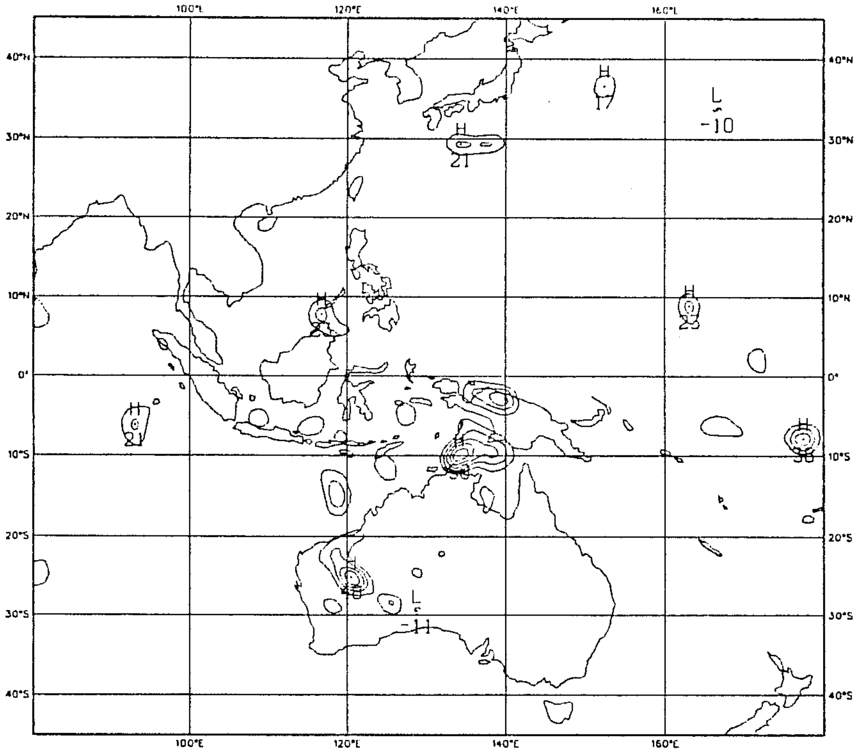
$$\frac{\partial T}{\partial t} = IH(p)$$

where I denotes the intensity of heating and H the vertical profile then from equation (2):

$$I = \frac{L}{C_p} \frac{\dot{R}}{\bar{H}}$$

where $\bar{H} = \int_{p_B}^{p_T} H(p) \, dp$

The profile H(p) in the current study was obtained from the vertical profiles of vertical velocity obtained from ECMWF analyses (Arpe, private communication). An example of a typical profile which is the mean profile for DJF 1986/1987 averaged over the domain 15°N-15°S, 140°E-200°E is presented in



500hPa Mean Hrate T106
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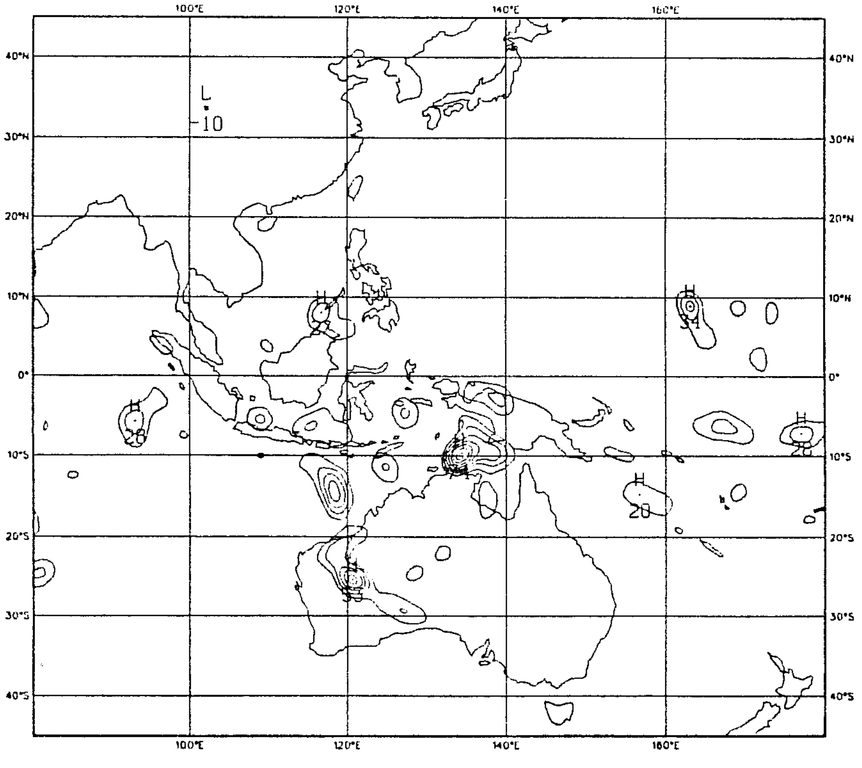

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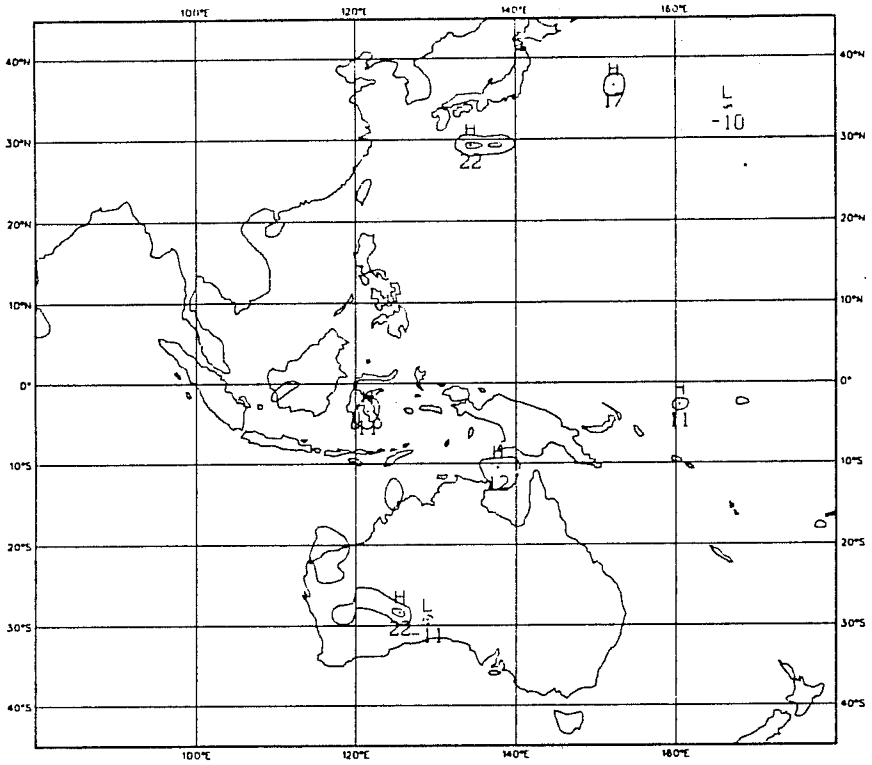
Fig. 5a Model generated heating rates at levels close to 50 hPa (top) and 200 hPa (bottom). Units are degrees day^{-1} and contour interval is 10° day^{-1}.



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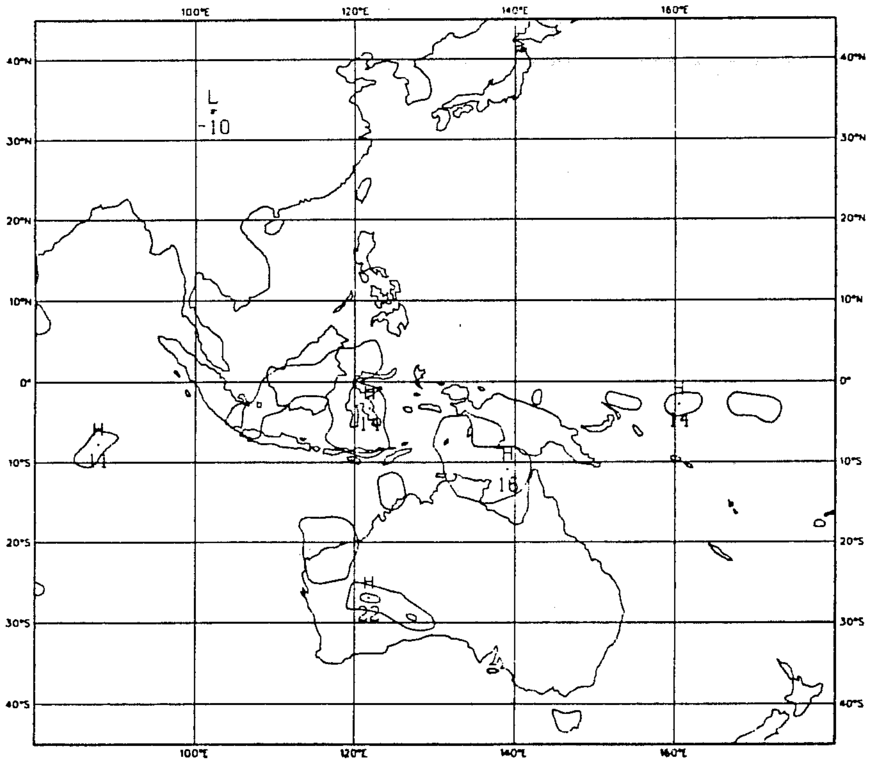

200hPa Mean Hrate T106
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Fig. 5b As in Fig. 5a but for heating rates derived from OLR data with specified heating profile.

Fig. 4 which shows the mean profiles for analyses at 00Z, 06Z, 12Z and 18Z. It should be noted here that Arpe has examined such profiles for several years of ECMWF analyses and found that although the intensities have varied from year to year, the shapes have not shown any major changes. An example of the heating rates obtained from the model and those obtained from OLR fluxes using the method described above are shown in Figs. 5a and b. Note that there is good agreement on the location of the major convective areas between the two schemes. However, the model generated heating rates are much stronger. Application of the time and space filter described above leads to good agreement in the location of convective centres with the model generated heating rates again being stronger.

In the method described above the same specified heating profile is used in the entire tropical belt. This constitutes a major shortcoming as it is known from observational evidence that the heating profiles can vary in location and could also depend on the stage in the life cycle of the convective system. One way of overcoming this limitation is to derive the heating rates to be compatible with the convective parametrization used in the model. Following the suggestion of Tiedtke (Personal communication) the procedure with the Kuo parametrization as used in the ECMWF model is as follows:

- Evaluate $\dot{R}$ from OLR data from expression 1 and convert it to units appropriate to those in the model;

- In the Kuo parametrization
  (a) Set the moisture convergence to be equal to $\dot{R} x 2\Delta t$, where Δt is the timestep used in the time integration

  (b) The moistening parameter b is set to 0 so that all the moisture convergence falls out as rain.

The Kuo scheme will now generate a heating rate which is consistent with both the model parametrization and OLR data.

Figs 6a and b show the model generated profiles and those obtained from the above procedure at two grid points, A(5.6°S, 120.4°E) and B(5.6°S, 131.6°E). Both points were chosen within the large area of precipitation north of

Australia as indicated by the OLR data (see Fig. 3). At point A both schemes generate substantial heating with the model heating rates stronger by factors of 2 to 3; the vertical structures are however similar. At point B the model heating rates are very weak implying weak convective activity which is inconsistent with the OLR data. This is an illustration of the use of OLR data to overcome one of the disadvantages of using model generated heating rates during diabatic NMI. The distribution of the heating rates at model levels close to 500 hPa and 200 hPa are shown in Figs. 7a and b. The model generated heating rates tend to be rather spotty and generally more intense that those obtained from the OLR data. Fig. 7a also illustrates another potential disadvantage of using model generated heating rates, which is the tendency of the model to generate grid point storms. The model has generated such a storm at about 20°S, 130°E with strong heating. This is clearly not supported by the OLR data and in fact is not present in Fig. 7b.

In summary, the results presented indicate that OLR data can be used to provide information about convective heating rates. Furthermore the procedures proposed for using this data have the potential of overcoming some of the disadvantages of using model generated heating in, for example, diabatic NMI. It should be noted that the procedures rely on obtaining reasonable estimates of the precipitation rates. The relation used to convert OLR data to precipitation rates which is based on monthly mean data probably does not apply to daily precipitation rates and provides a lower estimate. However, considerable effort is being devoted towards improving the estimates for instantaneous precipitation rates (see for example Adler and Negri, 1987 and references therein). Furthermore, DMSP satellites have the capability of providing improved estimates of rainfall rates as does the proposed Tropical Rainfall Measurement Mission (TRMM). There is also a reasonable rain gauge network over a number of countries in the tropics and more reliable estimates of the rainfall rates could be obtained by merging the conventional network with the satellites. Such a procedure has already been used by Krishnamurti et al. (1983).

The specification of appropriate heating rates for diabatic NMI in conjunction with the use divergent structure functions during analysis has the capability of producing an improved divergence field which is dynamically balanced through the use of diabatic NMI and is sensitive to the regions of convective

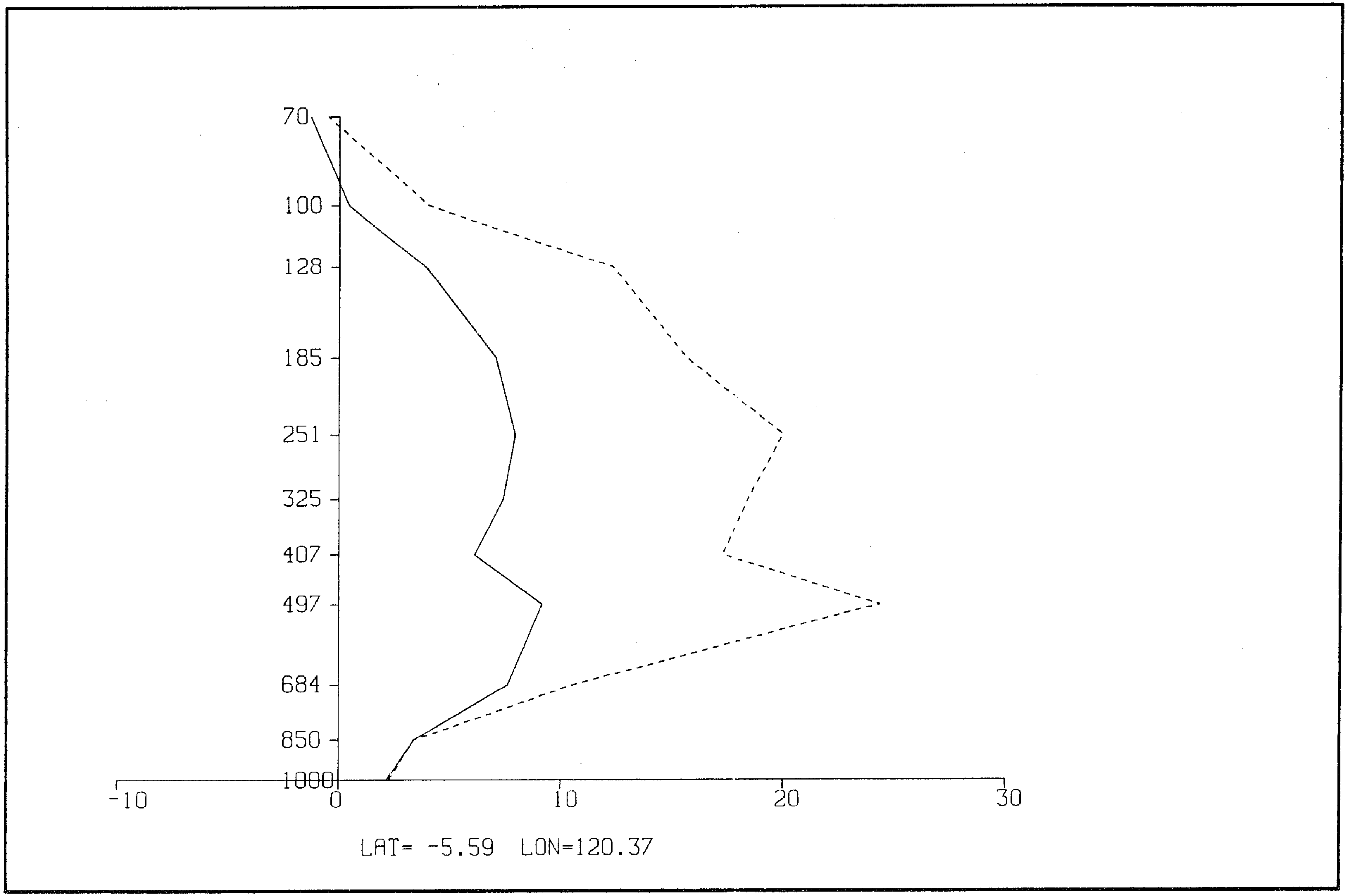

Fig. 6a Heating profiles in degrees day^{-1} at 5.6S, 120.4E. The dashed line denotes model generated heating rates while the full line denotes those obtained from OLR data using Kuo parametrization.

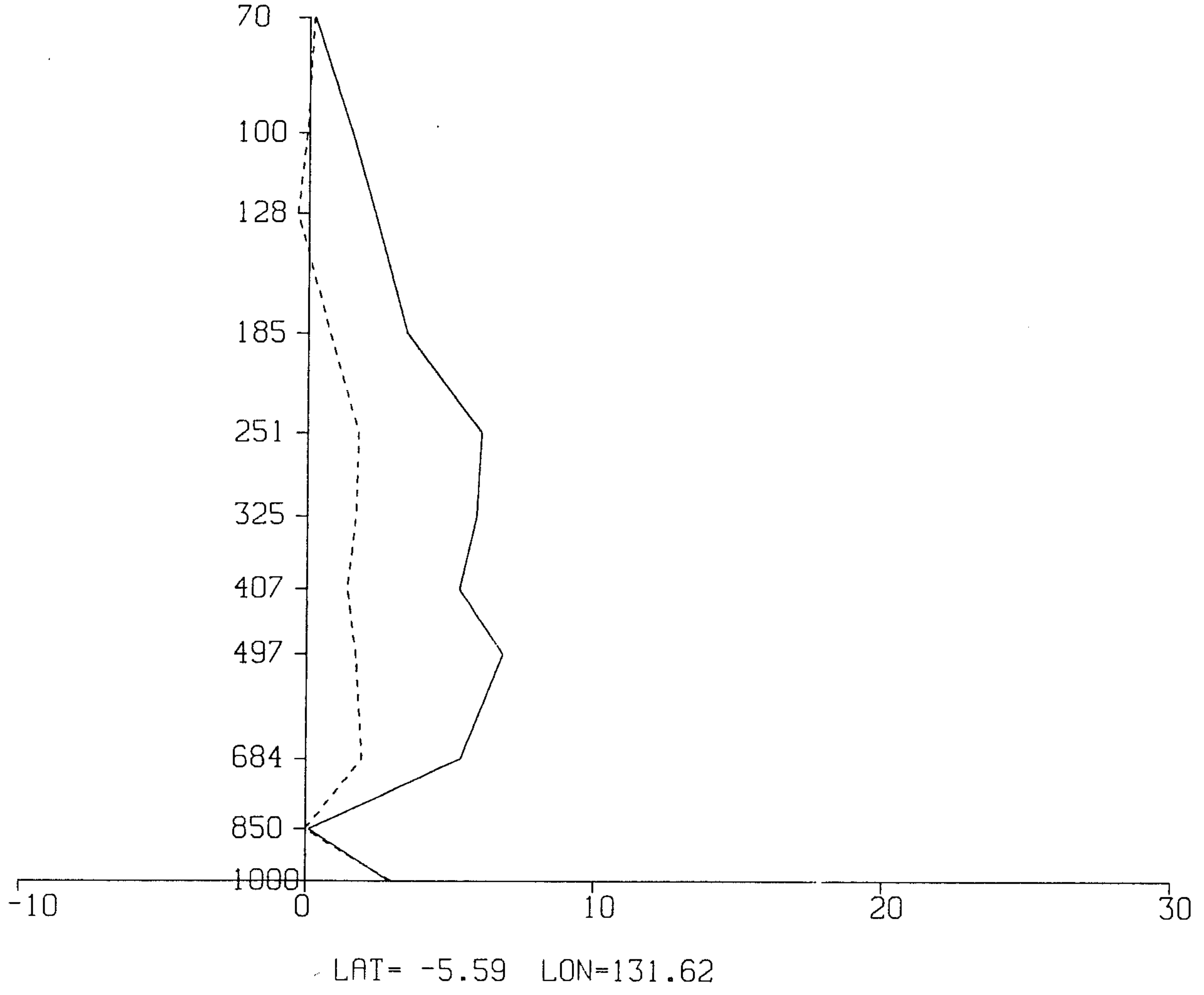

Fig. 6b As in Fig. 6a but for 5.6S, 131.6E.

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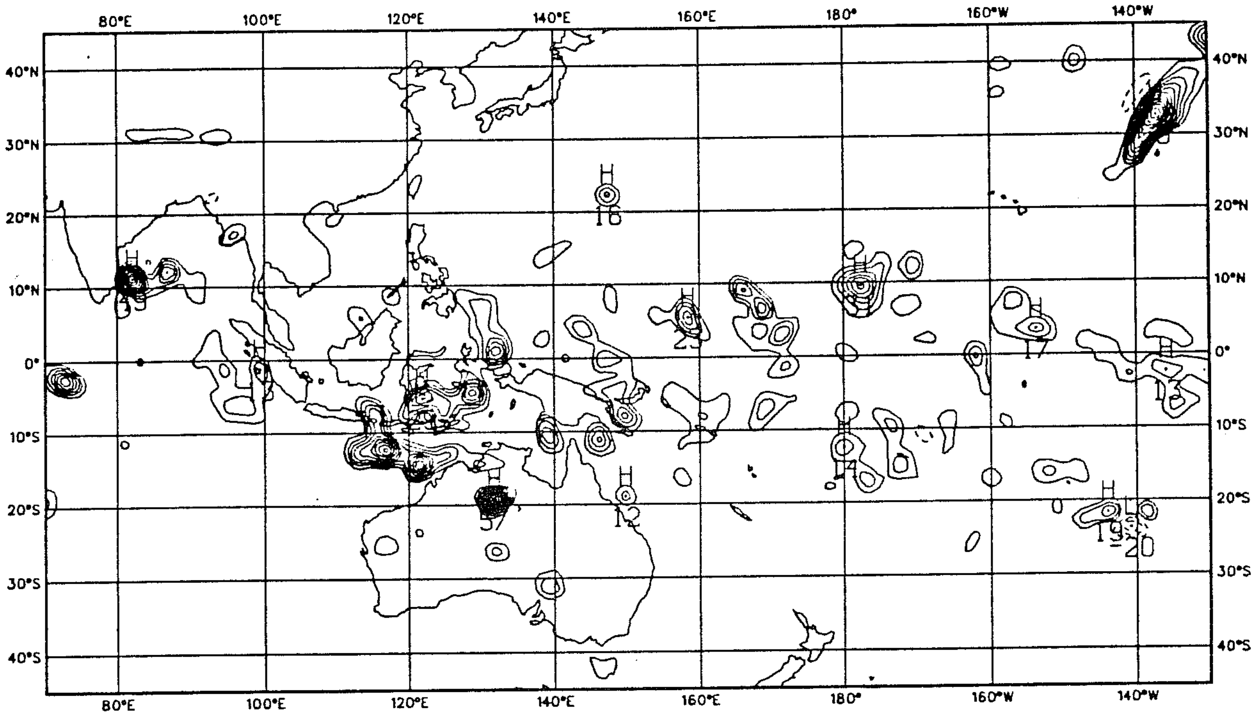

200hPa Mean Hrate T106
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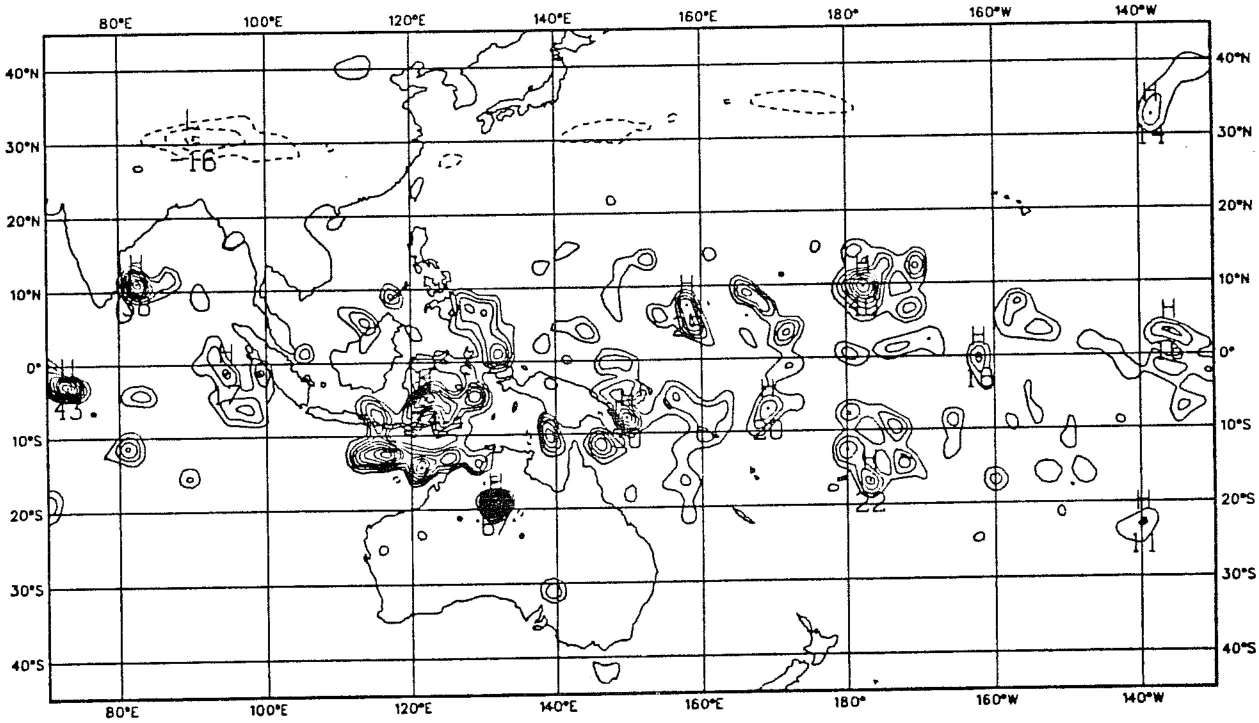

Fig. 7a Model generated heating rates at levels close to 500 hPa (top) and 200 hPa (bottom). Units are degrees day^{-1} and contour interval is 5° day^{-1}.

500hPa Mean Hrate T106
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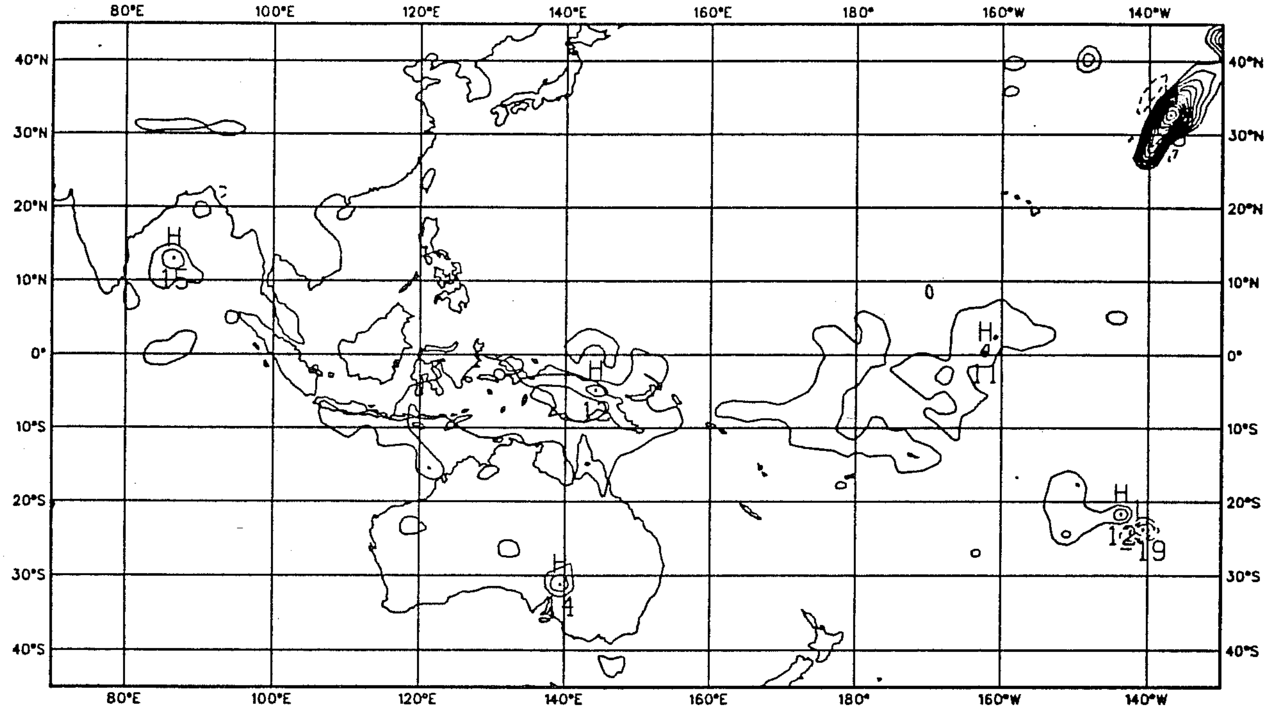

200hPa Mean Hrate T106
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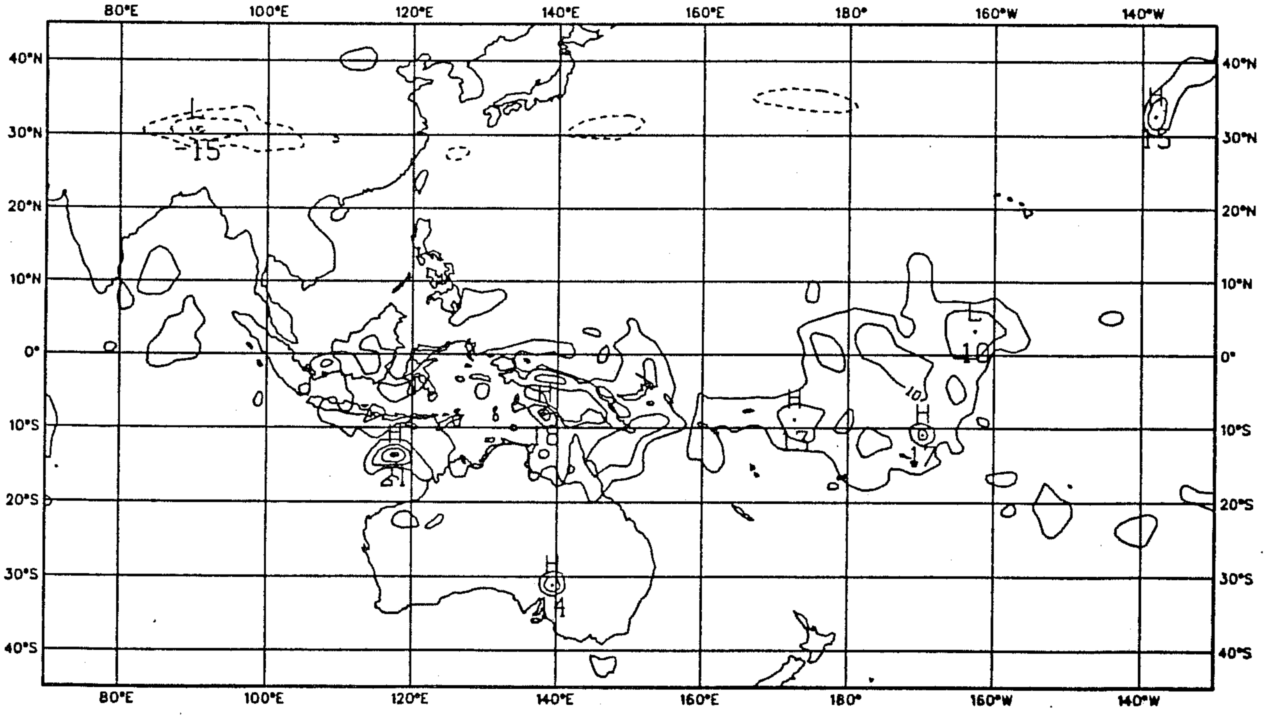

Fig. 7b As in Fig. 7a but for heating rates obtained from OLR data using Kuo parametrization.

heating. However, as was indicated earlier, the balance achieved during initialization can be rapidly lost if the heating rates in the early stages of the model forecast are not consistent with those used during initialization. This could occur if the analysis of the moisture field is deficient. One way of overcoming the problem is to adjust the initial moisture field and the following section will describe a procedure for achieving this.

4. INITIALIZATON OF THE MOISTURE FIELD

A considerable amount of work in this area has been conducted by Krishnamurti et al. (1983) who refer to this initialization as physical initialization. In their scheme the humidity analysis in the rain areas is restructured to the cumulus parametrization so that the initial computed rainfall rate is close to the observed rainfall which is obtained from a mix of rain gauge and satellite radiance information. Over the rain free areas, the humidity field is reanalysed to approach an advective radiation balance.

In this section a brief description of a moisture initialization based on the Betts-Miller (1984) adjustment scheme will be described. A more detailed report will be published elsewhere (Puri and Miller, 1988). The adjustment scheme is based on adjustment towards quasi equilibrium profiles of T and q and is designed to ensure adjustment to more realistic structures (T_r,q_r). The reference profile T_r is less stable than the moist adiabat in the lower troposphere and more stable above. q_r is computed so as to maintain subsaturation in a convective atmosphere. Subsaturation is obtained using a subsaturation pressure difference

$$\tilde{p} = p_* - p$$

where p_* is the pressure to which the parcel must be lifted to reach saturation.

The moisture initialization procedures involves the following steps:

- If $\dot{R}$ and $\dot{R}_m$ (both greater than 0) are defined as the observed and model precipitation rate, the latter being computed from a 1 time step model integration, we compute

  $\Delta R = \dot{R}_m - \dot{R}$

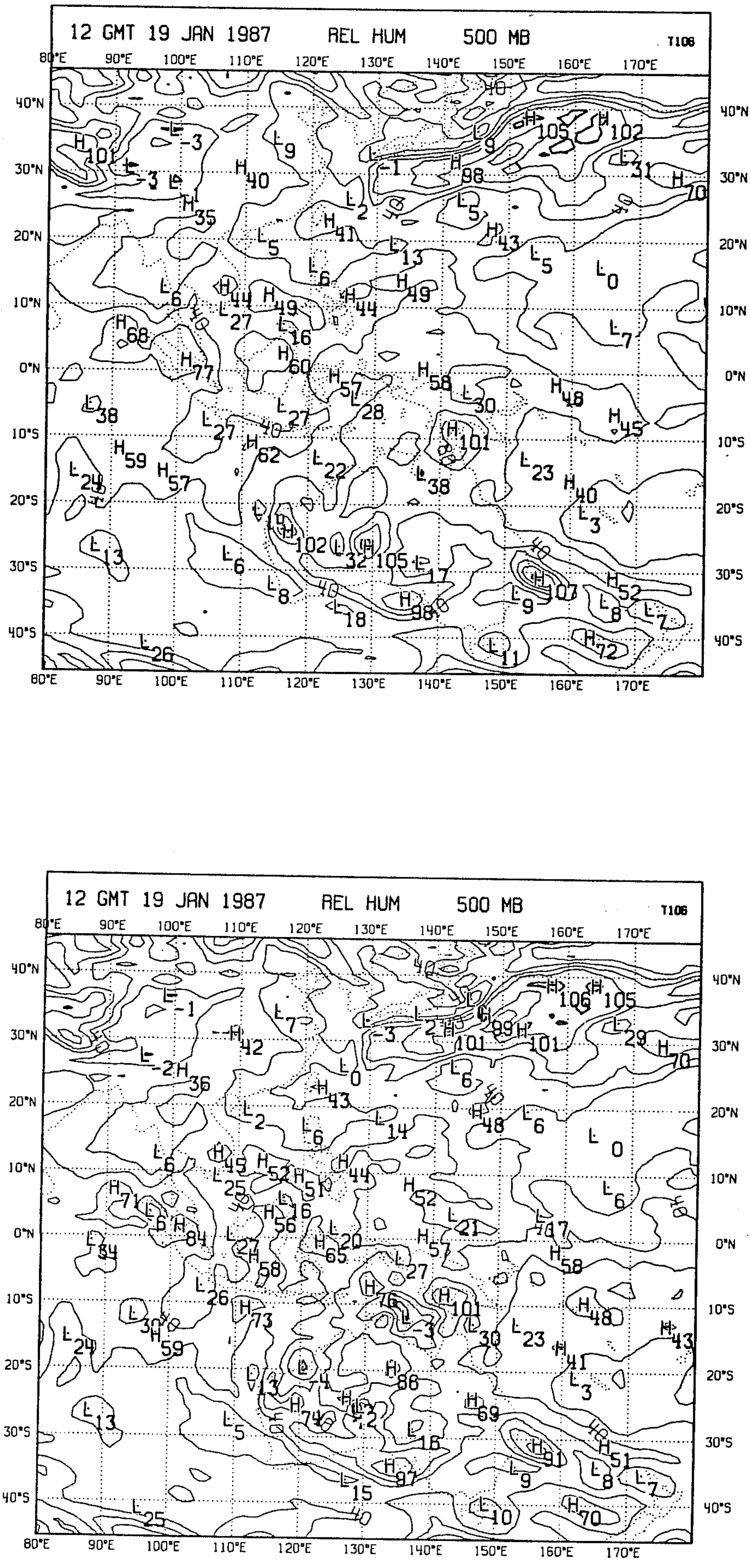

Fig. 8 Relative humidity at 500 hPa before (top) and after (bottom) moisture adjustment. Contour interval is 20%.

T106 ADJ-OLR RAIN
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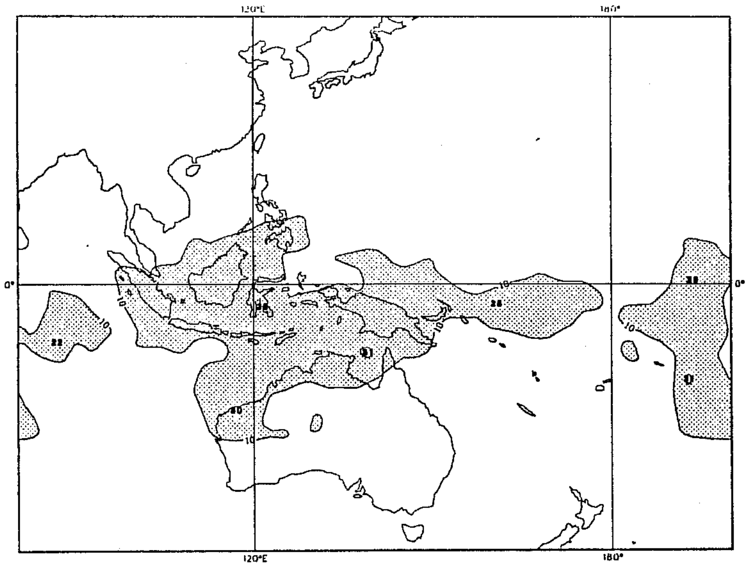
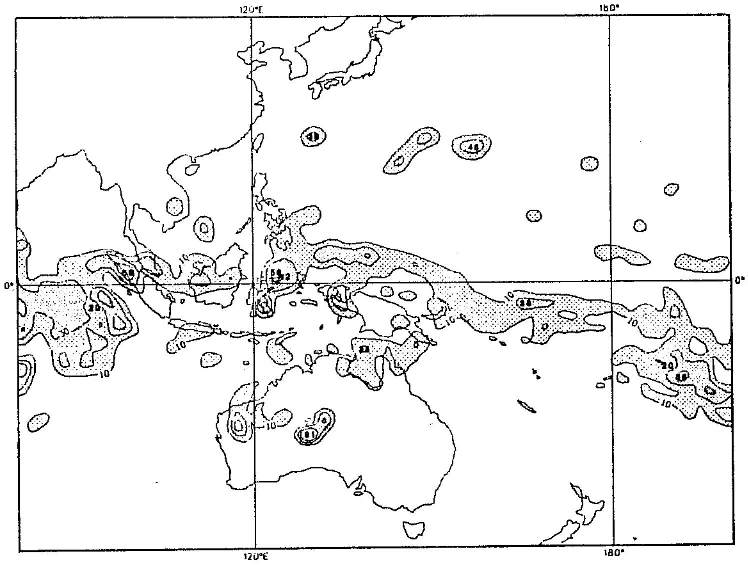


T106 ADJ-MODEL RAIN
DATE: 87011912



MDL RAIN ADJ BEFORE
Date: 87011912

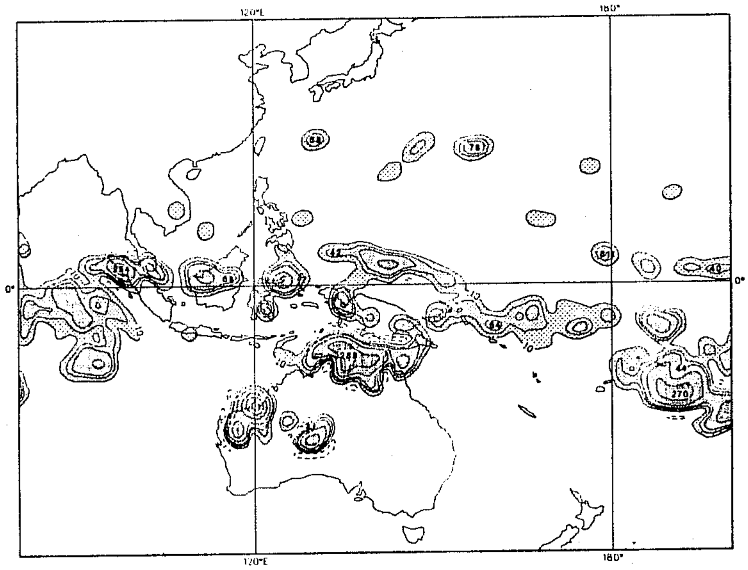


Fig. 9 Rainfall rates derived from OLR data (top) in mm day^{-1} and first time step of model integration from adjusted (middle) and unadjusted (bottom) moisture fields converted to mm day^{-1}. Contours shown are 10, 30, 50, 100, 200, 300 mm day^{-1}.

- Convert ΔR to $\Delta\tilde{p}$ using an empirical formula

- Use linear profiles of $\Delta\tilde{p}$ such that maximum change in $\Delta\tilde{p}$ is at freezing level and no change at cloud top or bottom

- Compute q_r^* using $\tilde{p}_r^* = \tilde{p}_r + \Delta\tilde{p}$

- The modified moisture is

$$\bar{q}^* = \bar{q} + (q_r - q_r^*)$$

where $\bar{q}$ denotes the initial moisture field. Note that the above correction is applied when $\dot{R}_m \lessgtr \dot{R}$ but the scheme cannot currently handle the situation where $\dot{R}_m = 0$ and $\dot{R} > 0$. This is a limitation of the scheme which will only operate in region or convective activity in the model.

The impact of the above procedure on the moisture field can be gauged from Fig. 8 which shows the relative humidity before and after moisture adjustment. The changes generally tend to be small except in regions such as the Gulf of Carpentaria (in North Australia) and around the western coast of Australia. Note also that the changes can be of either sign. Fig. 9 shows the impact of the moisture adjustment on the rainfall rate in the first time step of the model (converted to mm day^{-1}). The rainfall rate from the unadjusted fields tend to be excessive compared to the OLR derived rate while the rainfall from the adjusted fields tends to be closer in magnitude to the OLR rate. The pattern of the rainfall from the adjusted and unadjusted fields is similar because, as was indicated above, the moisture adjustment scheme only operates in regions where the model generates convective activity. Thus to the north of Australia there are regions of rainfall implied by the OLR data which are not present in the rainfall from the adjusted and unadjusted moisture fields.

A typical feature of the Betts-Miller adjustment scheme as used at ECMWF is that it lead to large amount of precipitation in the first few hours of the model integration. This so called spin-up problem can be seen in Fig. 10. The moisture adjustment procedure described here has the potential to reduce this spin-up. This can be seen in Fig. 11 which shows the 6 hour precipitation for two model integrations starting from unadjusted and

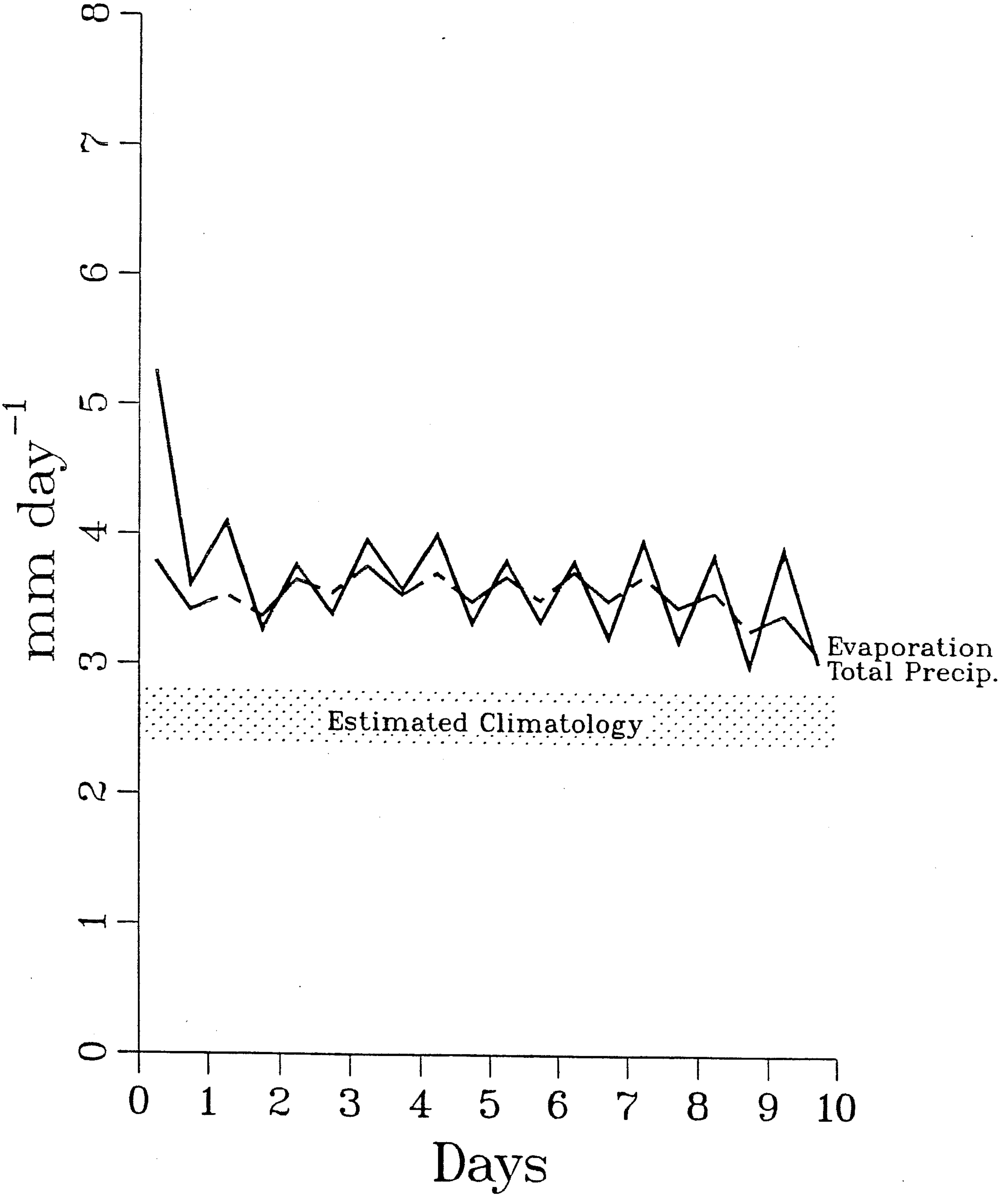
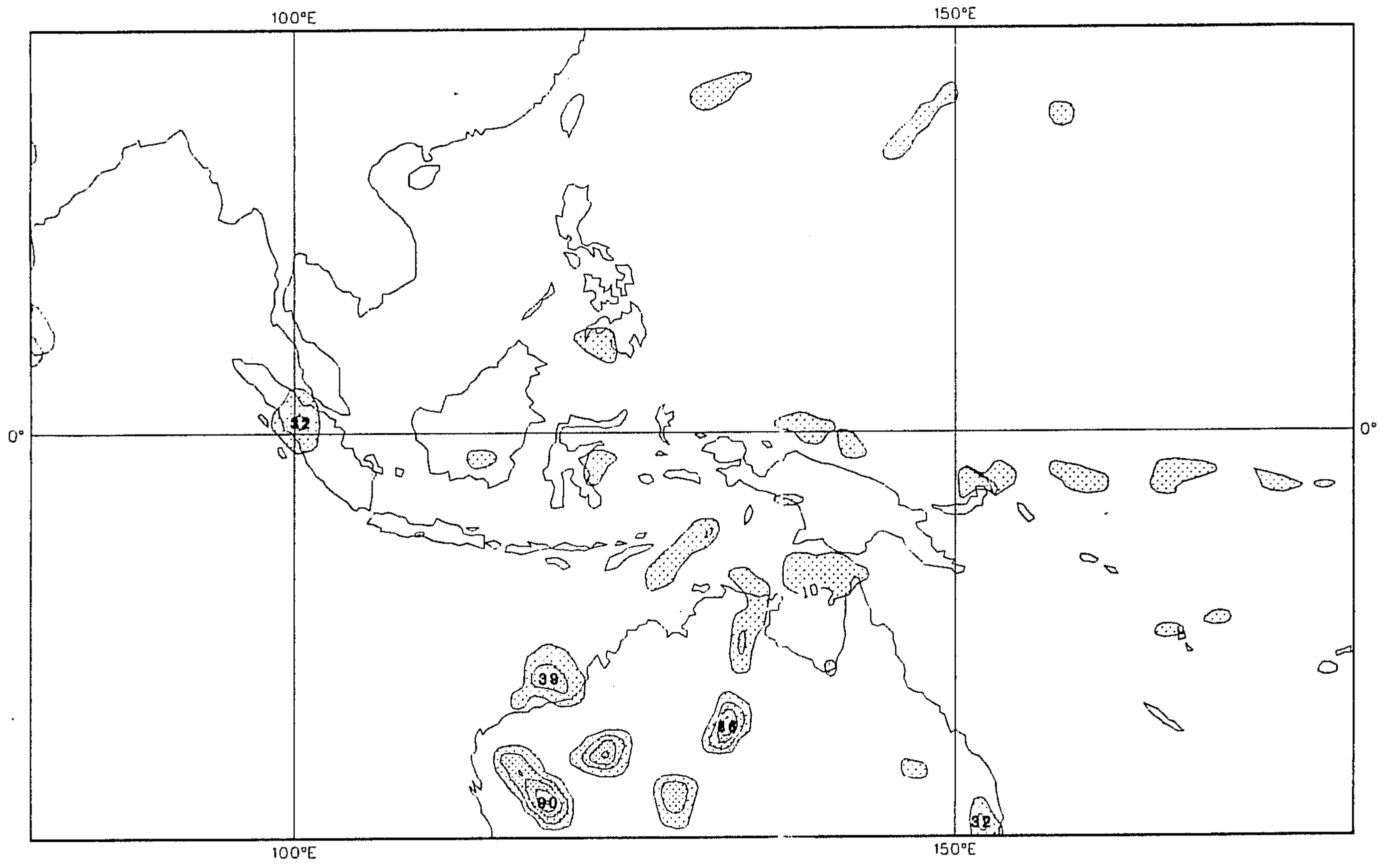


Fig. 10 Hydrological budget indicating typical spin-up signal in the Betts-Miller adjustment scheme as used at ECMWF.



Convective Precipitation 0-6 hours FMG

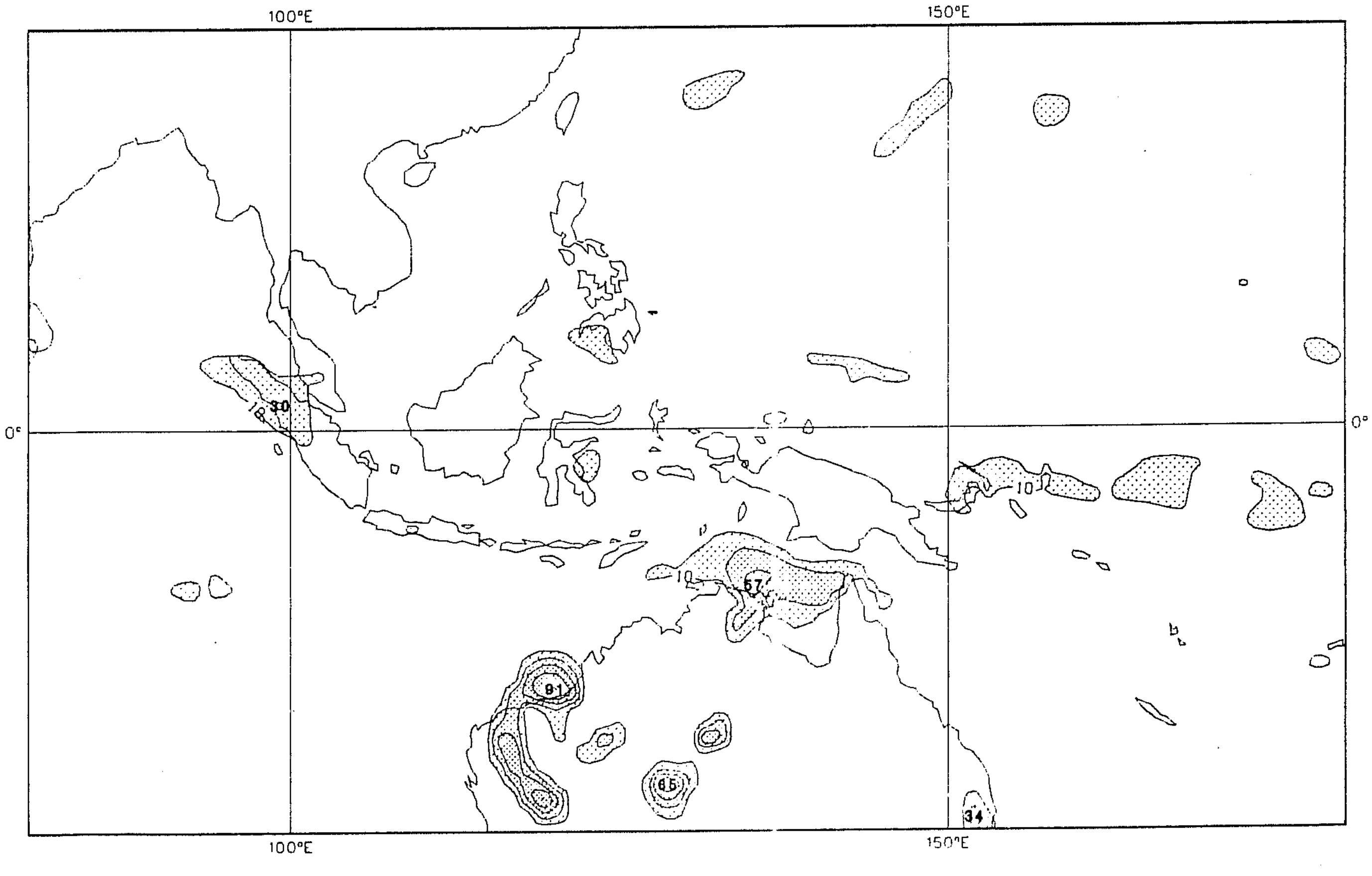


Fig. 11 Six hour precipitation in mm from model integrations from adjusted (top) and unadjusted (bottom) moisture fields. Contours shown are 10, 30, 50 and 70 mm.

adjusted moisture fields. The integration from the adjusted moisture field has significantly lower precipitation in the early stages of the model integration although the locations of the precipitation from the two integrations are rather similar.

5. CONCLUSIONS

Procedures to provide information about diabatic heating rates and to initialize the moisture fields from OLR data have been proposed. The heating rates deduced from the OLR data have the potential to overcome some of the disadvantages of using model generated heating rates in diabatic NMI. The specification of appropriate heating rates for diabatic NMI (in conjunction with the use of divergent structure functions during analysis) has the potential to generate improved divergence fields which are dynamically balanced and sensitive to regions of convective heating. This, together with the adjustment of moisture based on the same data, should lead to improved consistency between the heating rates used during initialization and in the early stages of the model integration.

Both procedures rely on obtaining reasonable estimates of precipitation rates. As was indicated above the relation used in this study to convert OLR data to precipitation rate is probably not appropriate. Given the potential benefits of the procedures proposed here, it is clear that much more work needs to be done towards improving the analysis of the rainfall rates. This could be achieved through improvement in the estimates from satellite information but will ultimately have to be based on a mix of conventional rainfall observations with satellite data.

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