PROBLEMS ASSOCIATED WITH THE PARAMETERIZATION OF DIABATIC HEATING AND RADIATION-CLOUD RELATIONSHIPS IN LOW LATITUDES

by

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1. INTRODUCTION

The primary energy source of the entire earth-atmosphere system is the incoming solar radiation. The major heat sink is the outgoing longwave stream. As the solar gain and the long-wave loss are not usually in local balance, energy transportation either directly or by implicit means is required in the zonal, vertical and meridional directions between regions of deficit and regions of energy excess. To accomplish the transport a variety of physical processes are invoked in an attempt to minimize the local imbalances. It is the aim of this note to define the role of diabatic processes in the accomplishment of the minimization with particular emphasis on the tropical regions. In order to do this we require the definition of the diabatic processes and a description of the associated systems.

The overall role of diabatic processes emerges from consideration of the global energy budget. If K represents the total kinetic energy of the system and P the available potential energy then we can write

$$\frac{dK}{dt} = \{P.K\} - E$$

and

$$\frac{dP}{dt} = - \{P.K\} + G$$

so that the total energy equation of the system is given by:

$$\frac{d}{dt} (K + P) = G - E \qquad (1)$$

where G and E are the available potential energy generation and kinetic energy dissipation terms. For a quasi-geostrophic system G may be written as:

$$G = - \int_V \frac{f_o^2}{\sigma} R \frac{\partial\psi}{\partial p} dv \qquad (2)$$

where f_o and σ are Coriolis and stability parameters, R the diabatic heating and $-\frac{\partial\psi}{\partial p}$ is a measure of the temperature of the column. $\int dv$ indicates a volume integration. (1) states that the rate of change of the total energy is given by the difference between the generation of available potential energy due to the correlation of diabatic heating (R) and the temperature $(-\frac{\partial\psi}{\partial p})$ and the kinetic energy dissipation by surface friction. The implication of (1) and (2) to numerical weather prediction is obvious and immediate. If R is large and is a consequence of processes existing on time scales similar to or less than the forecast period, then a sound knowledge of both G and E is necessary to facilitate an adequate energy conservation.

The problem is underlined to some extent in Fig.1 which shows the vertical distribution of the zonally averaged heating rates attributable to transport mechanisms as a function of latitude. Calculations were made using data from Oort and Rasmussen (1971) and Newell et al. (1972) for the northern hemisphere summer (i.e. June-August). At all latitudes the radiative cooling to space ($\dot{Q}_{RAD}$) and/or the condensational heating are major processes. Dynamic transports appear as small residuals. The profiles suggest that both the radiative effects and the condensational heating must be well-known in order to calculate the residual with some accuracy.

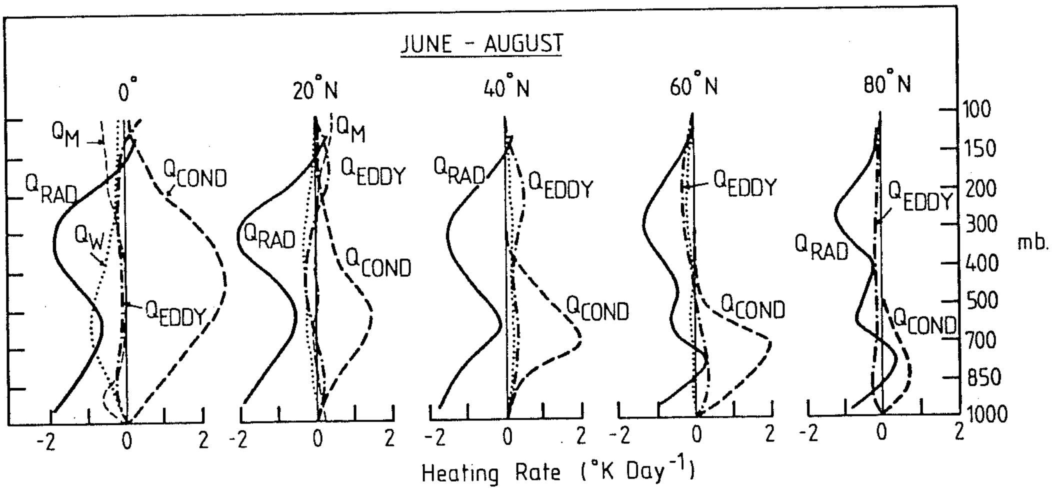

Fig. 1 Vertical distribution of heating rates attributable to zonally averaged transport mechanisms of various latitudes in July. Q_{RAD}, Q_{COND}, Q_M and Q_{EDDY} refer to heating due to radiation, condensation, mean motion heat convergences and eddy heat convergences.

The problem is compounded when the longitudinal or eddy structure of the diabatic heating is considered. If a zonal mean is defined ($\bar{\ }$) and a deviation from that zonal mean (') we may write down a mean available potential energy ($\bar{P}$) equation and an eddy available potential energy (P') equation. These are:

$$\frac{d\bar{P}}{dt} = -\{\bar{P}.P'\} - \{\bar{P}.\bar{K}\} + \{\underline{\bar{R}.\bar{P}}\} \qquad (3)$$

and

$$\frac{dP'}{dt} = \{\bar{P}.P'\} - \{P'.K'\} - \{\underline{P'.R'}\} \qquad (4)$$

The first two terms on the right-hand-sides of (3) and (4) refer to the energy conversions between the indicated energy forms. For our discussion the most important terms are underlined and refer to (respectively) the generation of mean zonal available potential energy and of eddy zonal available potential energy. The two terms are defined as

$$\{\bar{R}.\bar{P}\} = -\int_V \frac{f_o^2}{\sigma}\,\bar{R}\,\frac{\partial\bar{\psi}}{\partial p}\,dv \qquad (5)$$

and

$$\{R'.P'\} = \int_V \frac{f_o^2}{\sigma}\,R'\,\frac{\partial\psi'}{\partial p}\,dv \qquad (6)$$

(5) simply states that $\bar{P}$ is generated if mean zonally averaged diabatic heating correlates positively with the zonal mean temperature. As the net diabatic heating abundance occurs in the warm equatorial regions (i.e. latent, sensible and radiative effects) and the diabatic deficit occurs in the cool higher latitudes, then $\{\bar{R}.\bar{P}\}$ is positive. In a similar manner if eddy heating correlates with longitudinal variations in temperature then P' is generated (i.e. $-\{P'.R'\} < 0$). Oort and Rasmussen (1971) estimate by residual methods that $\{P'.R'\}$ is roughly 25% of $\{\bar{R}.\bar{P}\}$ in magnitude and 25% of either $\{\bar{P}.P'\}$ or $\{P'.K'\}$. Consequently the term is important from large scale energetic considerations.

Fig. 2 shows a partial representation of energy transports and heating rates for three locations (I, the arid regions of Saudi Arabia, II, the Arabian Sea and III, the Bay of Bengal). Radiational cooling is important at all the three adjacent locations but with a variation of form from the relatively dry and cloudless Arabian region to the moist, convective and cloudy Bay of Bengal.

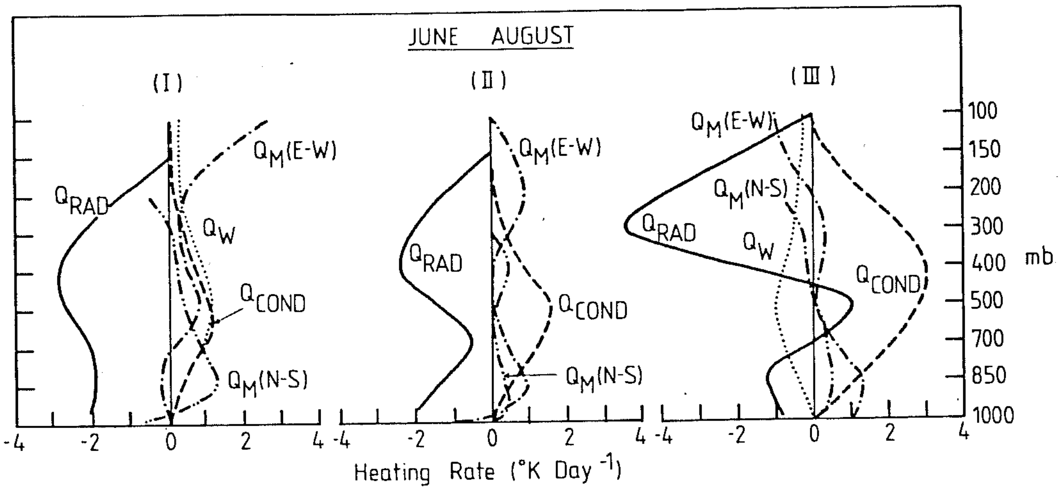

Fig. 2 Same as Fig.1 for heating rates along 25°N in July. Q_{RAD} and Q_{COND} Q_M(E-W) and Q_M(N-S) refer to heat convergences by zonal mean motions and meridional mean motion. Locations I, II and III refer to Saudi Arabia, the Arabian Sea and the Bay of Bengal.

Convective heating is maximized in the Bay of Bengal column and radiative cooling over the Arabian desert region. Large local imbalances between the radiational and condensational heating are apparent and the compensatory (longitudinal and latitudinal) dynamic transports are considerably larger than evident in Fig.1. What emerges are strong zonal and meridional transports ($\dot{Q}_M$(N-S) and $\dot{Q}_M$(E-W)) or, in other words, vigorous thermally forced dynamic modes.

The longitudinal variation of one diabatic heating component (radiative heating) is shown in Fig.3. Where the distribution of net radiative flux (positive into the atmosphere) at the top of the atmosphere using NIMBUS III data for July 1969 is plotted. The desert regions on the latitudinal section (small dashed curve) between 0^{O}E and 180^{O}E (upper abscissa scale) appears as net radiative heating sinks whereas the active convective region (80^{O}E - 180^{O}E) appear as net radiative heating sources. Most importantly, however, is that Fig.3 illustrates that the longitudinal gradient of the net radiation is equal in magnitude to the latitudinal gradient.

From Figs. (2) and (3) an obvious point arises. In order to simulate such circulation features described above (in this case the Asian monsoon) one requires the most careful representation of Q_{COND} and

Q_{RAD}. It is these balances (or imbalances) which determine the total diabatic heating fields, the generation of eddy available potential energy and, ultimately, the phase and amplitude of the long quasi-stationary features of the atmosphere which form the envelope within which weather resides.

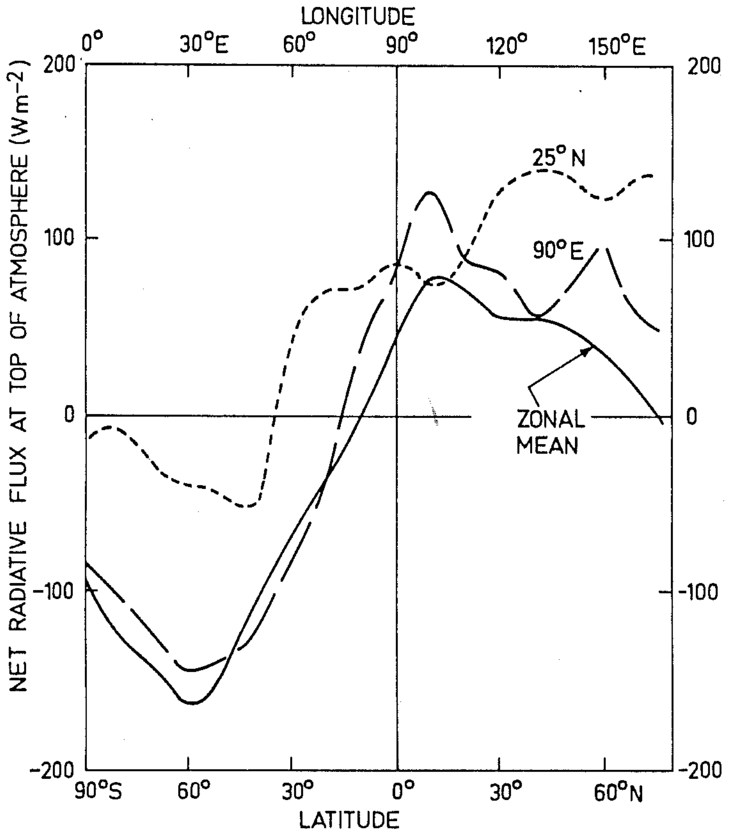

Fig.3. Net radiative flux at the top of the atmosphere as determined by NIMBUS 3 in July 1969. Shown are the pole-to-pole sections along 90°E, the zonal mean and a latitudinal section along 25°N between 0°E and 180°E. Net flux is positive into the atmosphere (from Stephens and Webster, 1979).

In the following discussion we will emphasize aspects of the radiational component of the total diabatic heating with particular emphasis on cloud-radiation relationships and cloud effect parameterization. Because of the importance of dissipation indicated in (1) a brief discussion of dissipational processes at low latitudes will be given.

2. ROLE OF CLOUD-RADIATION INTERACTIVE PROCESSES

Perhaps the most important modifier of the radiation budget of the climatic system on both local and planetary scales are clouds which possibly renders clouds and cloud-dominated processes as intrinsic features of the climate system. These are hinted at by the four basic mechanisms listed by Arakawa (1975) associated with clouds. These are:

(i) The coupling of dynamical and hydrological processes through the release of latent heat and evaporation, and by the redistribution of sensible and latent heat and momentum,

(ii) The coupling of radiative and dynamical-hydrological processes in the atmosphere through the reflection, absorption and emission of radiation,

(iii) The coupling of hydrological processes in the atmosphere and in the ground via precipitation, and,

(iv) the influencing of couplings between the atmosphere and the ground through modification of the radiation and turbulent transfers through the surface.

Most effort has been expended in attempting to parameterize the mechanism (i) which has met with some success, at least in the tropical convective regime (Ooyama, 1969; Anthes, 1977; Arakawa and Schubert, 1974 and many others).

Condensational heating adopts a myriad of forms depending upon the location within the atmosphere and the dynamic state of the atmosphere and coexists with non-convective as well as convective cloud systems. As the latent heating paramameterizations developed so far ignore an explicit knowledge of cloud distributions (generally utilizing a climatological radiation heating profile), they tacitly assume that mechanisms (i) and (ii) are independent or that radiational processes are unimportant. In other words, the neglect of explicit cloud distribution determination in the determination of the condensational heating (i.e. (i)) is only a good approximation if (ii), the effect of clouds on radiational heating is a small effect. However Stephens and Webster (1979, 1980) have emphasized a strong interdependency between (i) and (ii), thus questioning the practice of independent estimates of the two processes.

The radiative transfer model used for the determination of the short-wave fluxes is described in Stephens and Webster (1979) and the long-wave fluxes in Stephens and Webster (1980). Radiative properties of the clouds which were used in both studies emerge from the parameterizations developed by Stephens (1978) in which the effective long-wave emittance of the cloud and the cloud albedo are coupled via the liquid water path of the cloud. The relationships between the effective emittance and cloud albedo are shown in Fig.4. For relatively small liquid water paths the clouds become effectively black but do not achieve their maximum albedo unless the liquid water path is considerably larger. Consequently relatively low liquid water path clouds (e.g. high As and Cs) tend to be dominated by long-wave effects and thus tend to warm the surface of the earth. Large water path clouds (e.g. low level Cu or middle level Ns) tend to be dominated by short-wave reflection and consequently cool the surface.

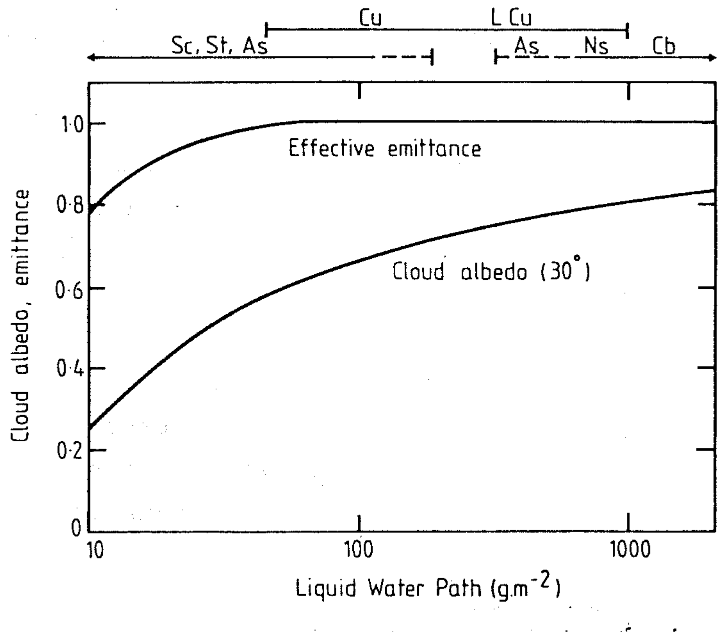

Fig. 4 Cloud albedo (zenith angle 30°) and cloud effective emittance as a function of liquid water path. Bars on the upper abscissa denote approximate radiative property limits of the various cloud species (from Stephens and Webster, 1980).

An example of the effect of various cloud types on the radiative structure of the atmosphere may be seen in Fig.5a. Calculated using the model developed by Stephens and Webster (1979), the change in net radiative flux into the atmospheric column between clear and overcast skies is described. The variation is shown as a function of latitude. It is interesting to note that the greatest difference in net radiative flux occurs at low latitudes for middle and high level cloud. While the results shown in Fig.5a are instructive it should be pointed out that they refer to a "fixed state" constraint. That is, the atmospheric structure was held constant and the radiative field which was consistent with that basic state and the imposed cloud was sought.

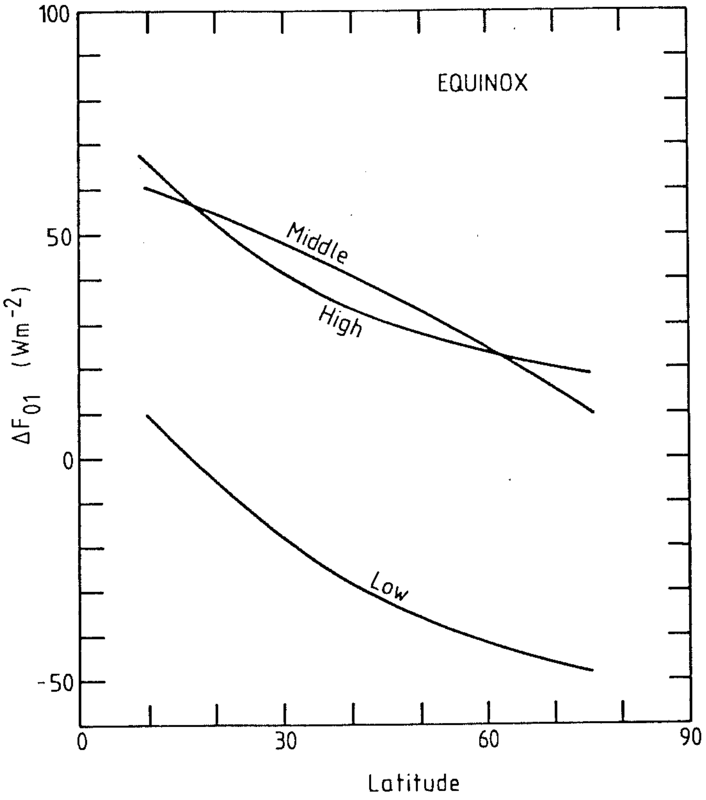

Fig. 5a Variation of net radiative flux in an atmospheric column between totally covered and clear skies as a function of latitude for three cloud species. Middle and low cloud fall roughly within the As, Cu range on Fig.4. High ice cloud emissivity and albedo values are listed in Stephens and Webster (1979). Diagram from Webster and Stephens (1980).

The results of Fig.5a are consistent with the calculations of the more sophisticated radiative-convective model of Stephens and Webster (1980) in which the atmospheric thermal state is allowed to adjust to equilibrium following the imposition of a cloud layer. Fig.5b shows the changes in equilibrium surface temperature for three latitude ranges between clear and overcast skies as a function of liquid water path. The albedo-emissivity parameterizations illustrated in Fig.4 were used in the calculations. Besides showing a strong dependency on cloud thickness, which may have been anticipated from Fig.4, the curves indicate a substantial influence of cloud base height at all latitudes and all liquid water paths (or, alternatively, cloud thickness). For a given water path the surface heating intensifies (or cooling reduces) with increasing cloud height due to the lower emitting temperature of the cloud top (Stephens and Webster, 1980). Thus, not only must an effective cloud parameterization forecast the cloud thickness, it must also determine the cloud base height.

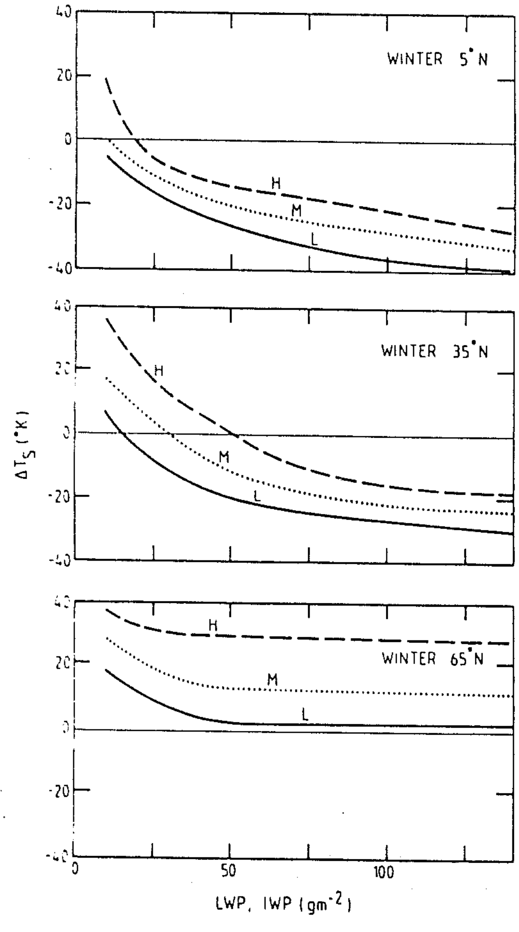

Fig. 5b Surface temperature difference (ΔTs) between clear and overcast conditions as a function of water or ice-water path (g m^{-2}) for three cloud layers occupying the slabs 913-854 mb (L), 632-549 mb (M) and 381-301 mb (H). Results are for 5°N, 35°N and 65°N in winter (from Stephens and Webster, 1980).

Figs. 6a and 6b show 5-day average cloudiness (tenths) for two periods (Dec. 02-06 and 07-011, 1978) compiled from data obtained from the Japanese Geostationary Satellite*. The two periods possess a number of common features. High cloud is concentrated in a narrow band about the equator and is associated with the upper level canopies of the equatorial disturbances. Both periods indicate a strong gradient in cloudiness between the equator and the subtropics and indicate that at low latitudes the predominant cloud species is upper level extended cloud. However, despite the similarities, the basic character of the distribution between the two periods is quite different. Thus if the calculations of Fig. 5 possess any merit, it can be expected that there may be substantial variation in space and in time of the basic radiative structure of the atmosphere and that this difference may be maximized at low latitudes. It is important to note that the time scale over which substantial variation of the distribution of cloud population occurs matches that of the forecasts produced by ECMWF.

With the above discussion in mind a clear implication emerges. If the variations in the basic radiative heating introduced by the cloud are comparable in magnitude to the other forms of diabatic heating, then they will contribute substantially to the energy generation terms shown in (2), (5) and (6). If this is proven to be the case then as considerable variations in cloudiness occur on time scales which match extended forecast limits, it would appear that interactive and well modelled cloud structures will be of paramount importance in extended forecast models.

Even though of all atmospheric constituents clouds have the potential of exercising maximum impact individually on both the long-wave and short-wave streams, the controversial question is whether or not clouds affect the <u>net</u> radiation stream. Cess (1976), for example, argues that the shortwave loss of energy due to cloud reflection is exactly balanced by long-wave enhancement by cloud absorption. However recent studies by Ohring and Clapp (1980)

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*More specifically from the Monthly Report of the Meteorological Satellite Centre", Tokyo, Japan, obtainable from the Japanese Meteorology Service (referred to as the JMSMR).

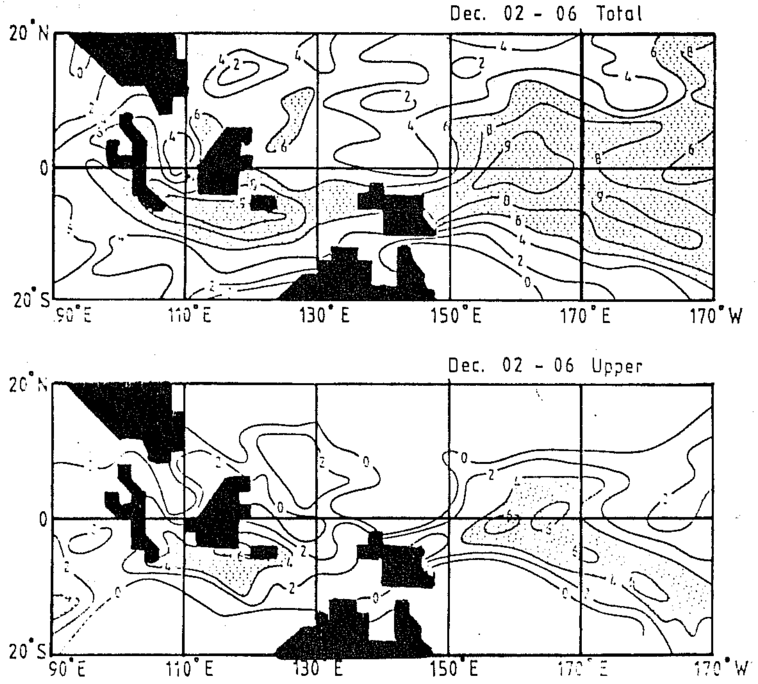

Fig. 6a Five day average cloudiness for total cloud cover (upper panel) and upper cloud (i.e. tops higher than 400 mb surface; lower panel). Shaded areas denote greater than .6 total cloud cover or .4 upper cloud cover. Period 02-06 December 1978.

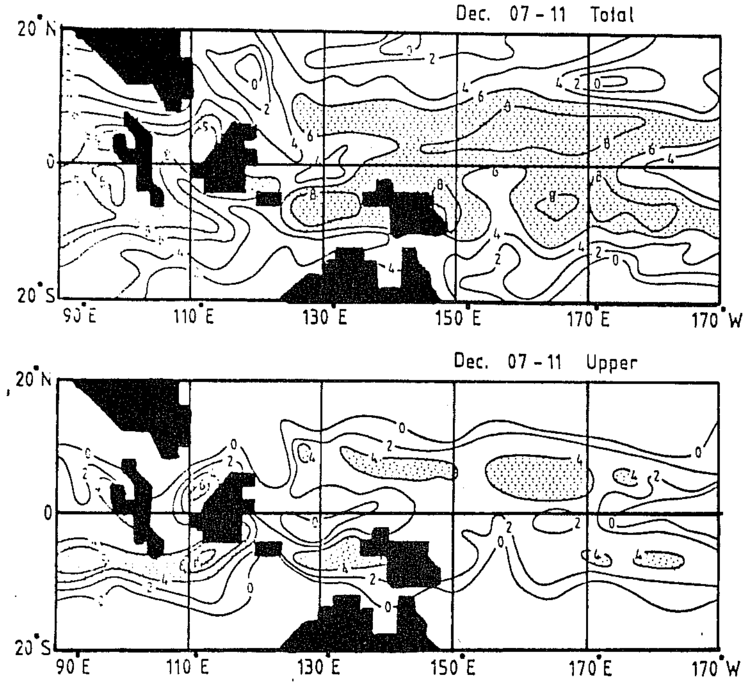

Fig. 6b Same as Fig. 6a except period is 07-11 December 1978.

suggest that the net radiation balance at the top of the atmosphere is sensitive to changes in cloud amount although Hartman and Short (1980) have shown that the quantities discussed by Cess and Ohring and Clapp are fundamentally different. For example Cess calculated a quantity like the total derivative of net flux with cloud amount (i.e. $\frac{dF}{d\theta}$)whilst Ohring and Clapp computed the sensitivity of the radiation balance to changes in cloudiness (i.e. $\frac{\partial F}{\partial \theta}$).

However, aimed principally at the planetary scale radiation budgets, neither the Ohring-Clapp or Cess study addresses the problem of regional or vertical energy redistributions by cloud. This is important as energy conversions and dynamic structures depend critically upon the vertical distribution of total diabatic heating to which radiational forcing may be a considerable contributor (Stephens and Wilson, 1979, Webster and Stephens, 1980). Consequently, the question of the impact of clouds on the net outgoing radiation flux at the top of the atmosphere may have only a partial relevance to the impact of clouds on the state of the system. Conceivably, the net flux at the top of the atmosphere is the least sensitive radiative quantity to changes in cloud amount. That is, a particular value of the net flux need not represent a unique state of the column below.

Thus, a definitive study of the cloud-dynamics feedback problem remains an elusive goal. Observational studies have been hampered by the need to establish "control" situations. Similarly, because of the multi-facetted interdependencies of cloud and climate, investigations by theoretical and numerical models are equally difficult and possibly premature with current models (G.E. Hunt et al. 1980). The utilization of simple energy balance models tends to be constrained by the simplicity of the adjunct radiation models and cloud parameterizations (see discussion by Stephens and Webster, 1979) and the neglect of all but the simplest dynamic transports.

At this stage we can at best point to theoretical or observational studies which place in a better perspective the relative scales of the various components of the diabatic heating.

3. COMPARISON OF THE SCALES OF THE COMPONENTS OF DIABATIC HEATING

A growing number of studies have indicated that the vertical radiative heating profiles between the disturbed and undisturbed regions are significantly different; the difference being basically attributable to cloudiness (e.g. Cox and Griffith, 1979; Albrecht and Cox, 1975; see also Fig. 2).

The relatively detailed data set which has emerged from the Winter Monsoon Experiment (held in the South China Sea region between December, 1978 and March, 1979) has allowed the identification of many of the features of the predominant upper level extended cloud noted in Fig. 6. The details of the associated atmospheric structure are described by Webster and Stephens (1980) and are summarized in Fig. 7 which shows the mean relative humidity (left panel) and the dew-point and temperature curves (right panel) for the disturbed period (15-17 December, 1978; dashed curves) and undisturbed period (7-9 December, 1978; solid curves). The most important feature of Fig. 7 is that the disturbed structure indicates a mid-tropospheric maximum which corresponds to deep middle level cloud noted in Fig. 6.

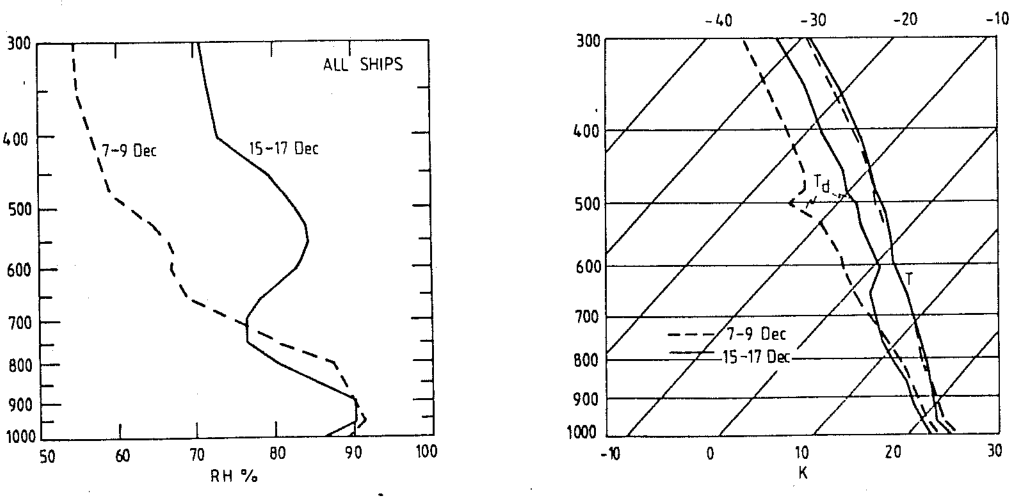

Fig. 7 Mean South China Sea disturbed (15-17 Dec., 1978) and undisturbed (7-9 Dec., 1978) relative humidity (left panel) and temperature and dewpoint (right panel) plotted against pressure (from Webster and Stephens, 1980).

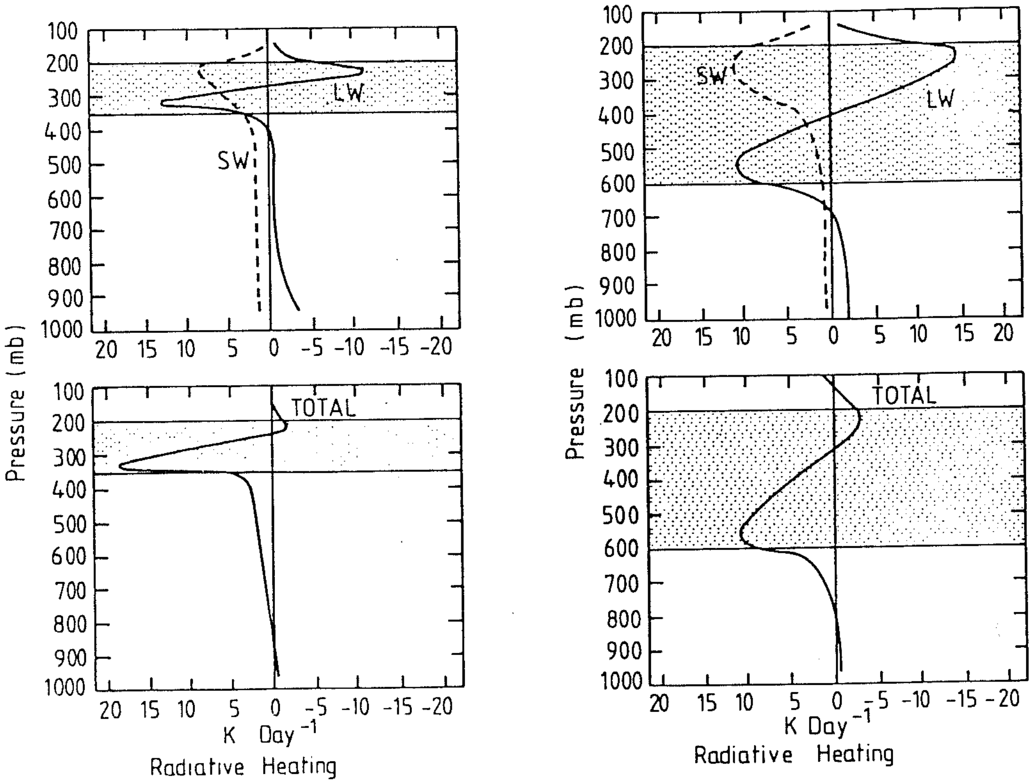

Fig. 8 Vertical distribution of radiative heating in the visible (dashed) and infrared (solid) range relative to a slab between 200-350 mb (left panel) and 200-550 mb (right panel). Data for the 200-550 mb slab obtained from the mean 15-17 December data shown in Fig. 7 (from Webster and Stephens, 1980).

With the cloud and atmospheric structure obtained from WMONEX it is possible to calculate the radiative heating profiles in the vertical for various cloud structures. To obtain the profiles we use the relatively sophisticated multiple scattering radiative transfer model (Model A) of Stephens (1978) which calculates both long- and short-wave fluxes through a cloudy atmosphere. The atmosphere is composed of 50 mb slabs extending from the surface to 100 mb and the basic atmospheric state was chosen to match the mean South China Sea conditions (see Fig. 4). The cloud portion was assumed to be in the ice phase and the thickness determined from the satellite derived cloud top height. The cloud bases were chosen to match those observed by the research aircraft.

Fig. 8 shows the vertical distribution of the infra-red heating rate (solid curve), the short-wave heating rate (dashed, and calculated using daily average insolation) and the total radiative heating rate for two clouds (shaded area) occupying the 600-200 mb slab, which matches the observations, and the 350-200 mb slab used for comparison. In each case, the effect of the cloud deck is dramatic in both the long- and short-wave regions. The short-wave radiative heating is due to the effective absorption of solar radiation by both cloud material and water vapour. The infrared heating at the base of the cloud underlines the effectiveness of an upper deck to absorb the ingoing long-wave radiation emanating from lower, warmer regions. That is, both systems are optically black. The long-wave structure in the upper portion of the cloud represents the distinct cooling to space.

The total effect of the radiative heating is to produce substantial heating in the lower part of the deck (approximately 20°K day^{-1}) with cooling at the top (about -15°K day). Such a result is in sharp contrast to the mean tropical heating rates of Dopplick (1972) (i.e. weak net cooling throughout the atmospheric column irrespective of cloudiness) but in agreement with Albrecht and Cox (1977) and Cox and Griffith (1979).

Integrating the heating with height shows for both cases a net heating throughout the slab and, incidentally, through the entire depth of the atmosphere. Considerable diurnal variation is also implied. During night time, the short-wave contribution is absent and the total heating curve matches the long-wave curve. Integrating once again with height, the total heating shows small net cooling both throughout the column and in the cloud.

With the summary of the radiative heating associated with the tropical cloud decks given in Fig. 8, we are now in a position to compare the magnitude of the components of the diabatic heating. For the latent heating we will rely on the estimates of Leary and Houze (1979) who calculated heating rates from radar data in the GATE experiment. The GATE systems of Leary and Houze are probably the best documented systems and at least allow the role of radiation to be assessed in conditions of intense convective and anvil precipitation. Their emphasis was with the extended cloud or anvil region of the disturbance from which they estimate some 40% of the total precipitation of the disturbance falls.

An important aspect of the total diabatic heating function is that it is a composite of functions of different signs. Latent effects tend to cool the lower part of the cloud (melting) and the sub-cloud layer (evaporation) and to heat the interior of the cloud. Conversely the radiative processes tend to warm the lower part of the cloud (absorption of upcoming infra-red radiation) and to cool the top (cooling to space, which is emphasized at night time due to the absence of solar radiation). Consequently, latent heating effects tend to stabilize the thermal structure of the cloud whereas radiative processes tend to destabilize the thermal structure. The important factor lies in the relative magnitude of the two component functions. Radiative processes will tend to remain constant for the same cloud structure; the magnitudes depend primarily on the cloud thickness (i.e. its optical blackness) and the cloud base height. On the other hand, the magnitude of the latent effects are strong functions of the intensity of anvil precipitation which, in turn, depends upon the intensity of the disturbance, the stage of its lifecycle and the distance of the atmospheric column from the convective source.

With these criteria in mind, it would appear that radiative processes will possess a varied importance depending upon the tropical disturbance in question or the particular location within the disturbance or its outflow region. For a vigorous disturbance such as Leary and Houze's case 1, which exhibited anvil precipitation of 8-9 mm hr^{-1}, radiative processes will almost certainly be of secondary importance in the total diabatic heat balance of the column. For disturbances 2 and 4 (precipitation rates of 0.3 and 2.3 mm hr^{-1} respectively) radiative heating at the base of the cloud tends to approach magnitudes which are similar to that of the latent heating due to melting. This is shown schematically in Fig. 9 where profiles of the two diabatic heating rates are drawn. For the average Leary-Houze disturbance the magnitude of the radiative heating is only 11% of the total cooling for melting and evaporation. For case 4 it accounts for 17% whereas for the weakest example of the set, case 2, the magnitude has risen to 33%. Thus with decreasing intensities the effect of radiative processes gain in importance and (conceivably) play an important role in the maintenance of the upper troposphere extended cloud system.

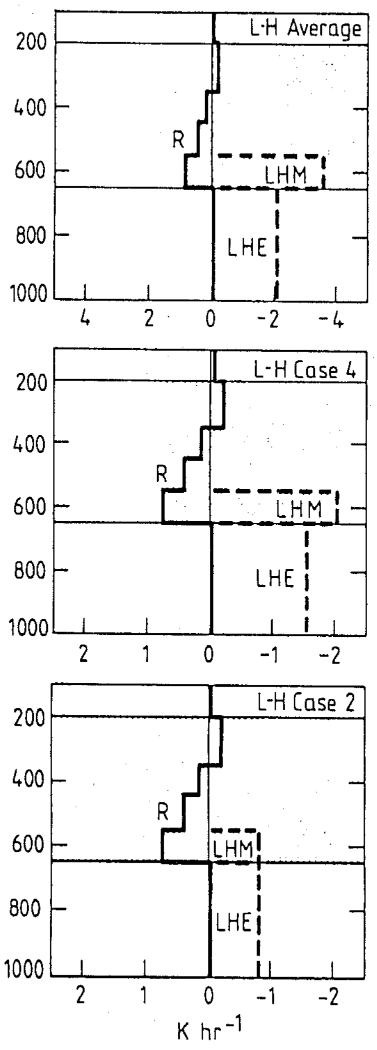

Fig. 9 Schematic comparison of diabatic heating rates for the average disturbance of Leary and Houze (1979) (upper) and their cases 4 (middle) and 2 (lower). R refers to radiative heating, LHE to cooling due to evaporation and LHM to cooling due to evaporation. Cloud slab extends from 200-650 mb. Note scale change between the upper and lower two panels. Units are °K hr^{-1}. From Webster and Stephens (1980).

4. OTHER PROBLEMS

In the preceding sections we have concentrated on the radiative aspect of diabatic heating and compared its magnitude in the tropical regions with the latent heating (cooling) of the atmosphere. The analysis has indicated a need for the careful consideration of radiation and radiation related processes for extended forecasts in tropical regions. However, we noted in the consideration of (1) that dissipation plays an important role in the energetics of the system.

Schneider and Lindzen (1976) and Stevens et al. (1977) have underlined the importance of "cumulus friction" or "cumulus damping". They have noted that the vertical momentum or vorticity transports by the cumulus clouds of disturbed systems impose a rapid damping time scale to tropical motions and are sufficiently important to remove the vertical structure of tropical waves. Using a damping timescale of days which matches the scales suggested by Stevens et al. Chang (1977) found that viscous effects introduced into the system a second class of modes. These modes possessed vertical scales similar to the depth of the troposphere; scales which were an order of magnitude greater than possessed by the invisid modes. The viscous class of modes were similar in character to many slowly evolving features observed in the tropical atmosphere, which dominate low latitude dynamics. In particular, Chang was able to identify many of the features of the Madden and Julian (1972) 40-50 day wave in the equatorial Pacific Ocean. The Madden-Julian mode would define a large percentage of the basic state of the low latitudes on medium-range forecasting time scales.

The importance of viscous effects in the disturbed tropical atmosphere places an added responsibility on the cumulus convection parameterizations. Not only must they relate the large-scale dynamics field to the cumulus- (or cluster-) scale latent heat release, they must adequately define the correct order of vertical momentum transport. Such effects must be taken into account in extended forecasting models as the cumulus damping time appears to fall well within the forecast period.

5. CONCLUSIONS

Radiative processes have been shown to be of some importance over a wide range of space and time scales. These processes appear to effect at least local balances in the total diabatic heating and consequently are manifested in dynamic structures of the atmosphere. Models of varying degrees of sophistication suggest that the radiative balance is greatly affected by cloud amount, cloud height and cloud type (i.e. water or ice) and that there influences are strong functions of latitude. Observations imply that substantial variations will occur in the radiative forcing of the atmosphere. Comparisons of the estimates of the radiative heating with latent heating calculations imply comparable magnitudes for the latent and radiative components of the total diabatic heating.

A clear implication for the problem of model parameterizations arises from the preceding points. It appears critical that all components of the total diabatic heating are calculated simultaneously. That is, a latent heat parameterization must, by necessity, contain a radiative component as this was shown to augment latent heat release in some situations but oppose it in other circumstances. Furthermore, it is necessary to parameterize carefully energy dissipation. In low-latitudes it appears that dissipation is closely associated with those processes which produce the maximum latent heat release and, at the same time, produce the radiatively important middle- and upper-tropospheric extended cloud. Clearly, there is a distinct need to incorporate interactive cloud parameterizations which include the four basic mechanisms suggested by Arakawa (1975) which are listed in Section 2.

However from a theoretical and practical viewpoint there still exist a number of major obstacles which complicate the task of parameterization. For example, it is doubtful if models could ever attain an accuracy which will describe adequately thin clouds and thus minimize the large error attributable to their rapidly changing properties (see Figs. 5 and 5b). However, Stephens' (1978) parameterization does suggest that the long- and short-wave properties of thicker clouds do approach almost constant values with increasing liquid water path. But at all thicknesses the radiative properties of the atmospheric column depend greatly on the height of the cloud and it is difficult to envisage cloud heights being simulated without introducing considerable error into the radiative heating field.

Even if cloud height, cloud amount and cloud type were adequately determined by the model there is still the problem of the effects of the numerics of the model on the resulting radiation fields. For example, over a large part of the tropical atmosphere, the radiative profile would be similar to that shown in Fig.8. Given the vertical resolution of the present numerical weather prediction models, the radiative heating and cooling maxima would, at best, appear at adjacent points in the vertical grid scheme. Such gradients are usually rapidly filtered and with that filtering the major physical impact of clouds on the radiation field at low latitudes would be minimized.

In summary, it appears that radiation and related processes are of some importance, especially in low latitude systems. However it is not obvious how these processes can be handled by explicit parameterizations. Perhaps an adequate treatment of radiative component of total diabatic heating, or even the total diabatic heating itself, requires the adoption of an alternative, or implicit, approach.

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