PARAMETRIZATION OF CONVECTIVE MOMENTUM TRANSPORTS IN THE ECMWF MODEL : EVALUATION USING CLOUD RESOLVING MODELS AND IMPACT UPON MODEL CLIMATE

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1. INTRODUCTION

A core aim of GCSS is the use of cloud resolving models (CRMs) to evaluate and develop convective parametrizations for use in general circulation models (GCMs). This is envisaged to be carried out in the context of single column models (SCMs), representing a single grid point of a GCM, provided with the same initial conditions and forcings as the CRM. This method is not new having previously been used by several authors to evaluate the performance of convection schemes using data from observations studies (*Betts and Miller* (1986), *Tiedtke* (1989), *Gregory and Rowntree* (1990)). However CRMs are able to provide information not easily obtained from observing experiments (for example updraught and downdraught mass fluxes) and so provide additional insight into the accuracy of the physical representation provided by convection schemes.

One area of convective parametrizations which can benefit from this approach is the representation of vertical transports of horizontal momentum by convective clouds. This paper describes the method used to represent convective momentum transports in the ECMWF model and evaluates the schemes performance using CRM data, parallelling the study of *Gregory et al* (1997) (hereafter referred to as GKI97) which used to same data to develop a convective momentum transport parametrization for use in the UK Meteorological Office Unified Model. Although the convective momentum transports scheme has been included into the ECMWF model since the late 1980s, with positive impact upon model performance, it has not been possible to carry out a detailed evaluation of its performance due to lack of observational or CRM data. The impact of convective momentum transports upon the climatology of the ECMWF model is also briefly described and contrasted with previous studies using other models. Finally brief comments are made concerning the impact of cloud organisation upon convective momentum transports.

2. THE PARAMETRIZATION OF CONVECTIVE MOMENTUM TRANSPORTS

Within the mass flux concept, the direct impact of convection upon the large-scale horizontal wind (denoted by Q3) can be expressed as,

$$Q3=\frac{D\overline{V}}{Dt}=\left(-\frac{\partial\overline{u'\omega'}}{\partial p},-\frac{\partial\overline{v'\omega'}}{\partial p}\right) \qquad (1)$$

where for u (and similarly for v)

$$\overline{u'\omega'}=M^{u}(\overline{u}^{u}-\overline{u})+M^{d}(\overline{u}^{d}-\overline{u}) \qquad (2)$$

M^u and M^d being the convective updraught and downdraught mass fluxes.

Of importance to a successful representation of convective momentum transports is the estimation of the in-cloud wind field. *Schneider and Lindzen* (1976) assumed that ascent within a cloud was sufficiently rapid to allow the in-cloud winds to be kept at the inflow value throughout the ascent. Work by *Shaperio and Stevens* (1980) included the effects of entrainment upon in-clouds winds, adjusting them back towards their large-scale values. However observational studies of deep convective systems (for example *Le Mone*, 1983) demonstrated that across cloud horizontal pressure gradients play an important role in modifying the in-cloud winds as air ascends.

While several authors have noted the importance of the across cloud pressure gradient *(Konig and Ruprecht* (1988) and *Zhang and Cho* (1991a,b)) and developed methods to account for the impact of these upon parametrized convective momentum transports, these schemes were not well validated due to poor observational data. Recent work presented by *Kershaw and Gregory* (1997) (hereafter referred to as KG97) and GKI97 has attempted to improve on these previous studies by using CRM data, diagnosing the magnitude and vertical variation of the across cloud pressure gradient forcing for two convective regimes (described below) in which the convection was unorganised. They found that an adequate representation of the across cloud pressure gradient for updraughts and downdraughts was,

$$g\sigma^{u}\overline{\frac{\partial h}{\partial x}}^{u}=C^{u}M^{u}\frac{\partial\overline{u}}{\partial p} \qquad (3)$$

where C^u is a coefficient determined empirically. This form is similar to one suggested by *Rotunno and Klemp* (1982) from a linear analysis of the pressure perturbation across an isolated updraught.

The convective momentum transports predicted by a version of the UKMO convection scheme (*Gregory and Rowntree*, 1990) with this formulation of across cloud pressure gradients included agreed well with those estimated from the CRM for cases of a cold air out break (surface forced convection in linear shear) and GATE (deep convection in the presence of a low level jet and large-scale vertical ascent). The reader is referred to GKI97 for further details.

3. EVALUATION OF THE ECMWF PARAMETRIZATION OF CONVECTIVE MOMENTUM TRANSPORTS

3.1 Description of scheme

The mass flux convection scheme incorporated into the ECMWF model in the late 1980s (described by *Tiedtke*, 1989) included a representation of convective momentum transports. However in-cloud horizontal wind was only modified through entrainment of environmental air, the influence of across cloud pressure gradients being neglected. Later versions of the scheme (including the current operational version) were modified to take account of the pressure gradient effects in a simple manner by increasing the entrainment and detrainment rates for the estimation of in-cloud wind during the ascent of air through a cloud;

$$\frac{\partial M^{u}\overline{u}^{u}}{\partial p} = \epsilon^{u}M^{u}\overline{u} - \mu^{u}M_{u}\overline{u}^{u} + g\sigma^{u}\overline{\frac{\partial h}{\partial x}} \tag{4}$$

where

$$g\sigma^{u}\overline{\frac{\partial h}{\partial x}}^{u} = C(\mu^{u}M^{u}\overline{u} - \mu^{u}M_{u}\overline{u}^{u}) \tag{5}$$

and ϵ and μ are entrainment and detrainment rates. The value of C depends upon the type of convection. For deep and mid-level convection, C=2 (or 3 if ϵ=0) while for shallow convection C=0 (or 1 if ϵ=0). The value of C is also modified by the constraint that the detrainment rates needs to less or equal to the convective mass flux. The lower value for shallow convection reflects the fact that horizontal pressure gradients across shallow convection are small. The value of C was chosen to maintain the in-cloud to large-scale wind difference on the order of 1-2m/s (Miller, personal communication), similar to that suggested by cloud resolving model studies. Increasing entrainment and detrainment rates by the same amount ensures mass continuity for the ascending plume. Horizontal momentum is also transported in the vertical by the downdraught but horizontal pressure gradients are neglected, i.e. C=0.

3.2 Description of cases

The above parametrization of convective momentum transports used in the ECMWF model is evaluated for the two convective regimes (summarized in table 1 and 2) considered by KG97 and GKI97 (too which the reader is referred for more details). The first case is an idealised cold air out break where the convection is forced by surface fluxes ($S=123Wm^{-2}$, $LE=492Wm^{-2}$) and grows under a linearly increasing westerly shear (from 0 to 10m/s at 6km). Secondly, and more briefly, tropical convection growing in the presence of a westerly low level jet (horizontal wind increasing to 10m/s at 3km and decreasing to zero at 6km) with forcing (cooling and moistening) due to large-scale ascent and surface fluxes (S=12Wm-2, LE=143Wm-2). This later case is based upon data from the GATE experiment. It should be noted that in both cases the convection simulated by the CRM showed no large degree of organisation and so the results discussed below pertain to unorganised convection.

Single Column Model Experiment	Parallel Cloud Resolving Model Experiment	Shear (m/s/6km)	Surface latent heat flux (W/m^2)	Surface sensible heat flux (W/m^2)
E32	232	10	492	123
E33	233	20	492	123
E36	236	10	985	123
E37	237	20	985	123

Table 1 List of cold-air outbreak experiments

Single Column Model Experiment	Parallel Cloud Resolving Model Experiment	Surface latent heat flux (W/m^2)	Surface sensible heat flux (W/m^2)
E35	235	145	12

Table 2 List of tropical experiments

3.3 Overview of single column model and convection scheme

The single column model is based upon the physics of the full ECMWF model, although the convection scheme has been modified as described below. In this study surface fluxes are specified and the effects of radiation are neglected. The models initial conditions and large-scale forcing are identical to those used in the CRM simulations, the length of the experiments being 10 hours. Experiments carried out using the single column model have the same identification number as for the CRM simulation, but the first digit ("2") is replaced by an "E".

The convection scheme used in this study is a development of the bulk mass flux scheme described by *Tiedtke* (1989). In the original scheme, the cloud base mass flux is estimated through an assumption of boundary layer quasi-equilibrium (*Raymond*, 1995) on either moisture (deep convection) or moist static energy (shallow convection). The choice between deep and shallow convection is made on the basis of whether the moisture convergence into a column of the atmosphere is greater than surface evaporation. In the revised scheme, the estimation of cloud base mass flux for deep convection has been changed to one based upon the assumption that convection reduces Convective Available Potential Energy (CAPE) back to zero over a specified timescale (here 2 hours), being based upon earlier work by Nordeng (1994) following *Fritsch and Chappel* (1980). However, **unlike** the version of the scheme described by *Nordeng* (1994), the distinction between deep and shallow convection is made on the basis of cloud depth; if the cloud depth is greater than 200mb then convection is deemed to be deep and the CAPE adjustment closure is used. If the cloud depth is lower than this critical value then it is assumed to be shallow convection and the boundary layer quasi-equilibrium closure of the original scheme is used. The change from a moisture convergence to a depth switch to determine the presence of deep convection improves the simulation of surface forced deep convection such as in the cold air outbreak case here.

3.4 Cold air outbreak simulations

From equation (2), in the mass flux framework, the vertical flux of momentum by convection is determined by the convective mass flux and the difference between the in-cloud and large-scale wind. Figure 1 compared the updraught and downdraught mass fluxes estimated by the parametrization scheme for simulation E32 (10 hour average), compared to those diagnosed from CRM simulation 232. The magnitude, vertical distribution and depth of the parametrized updraught mass flux is in reasonable agreement with that found in the CRM, although underestimated in the lower troposphere. This is partially caused by the downdraught being under active in the parametrization compared to that in the CRM. The net mass flux predicted by the parametrization scheme is in good agreement with that in the CRM simulation.

Figure 2a compares the horizontal wind in the updraughts and large-scale wind for the same case from the single column model, figure 2b showing the same fields from the CRM simulations. The vertical profile of the wind in the parametrized updraught is in good agreement with that diagnosed from the

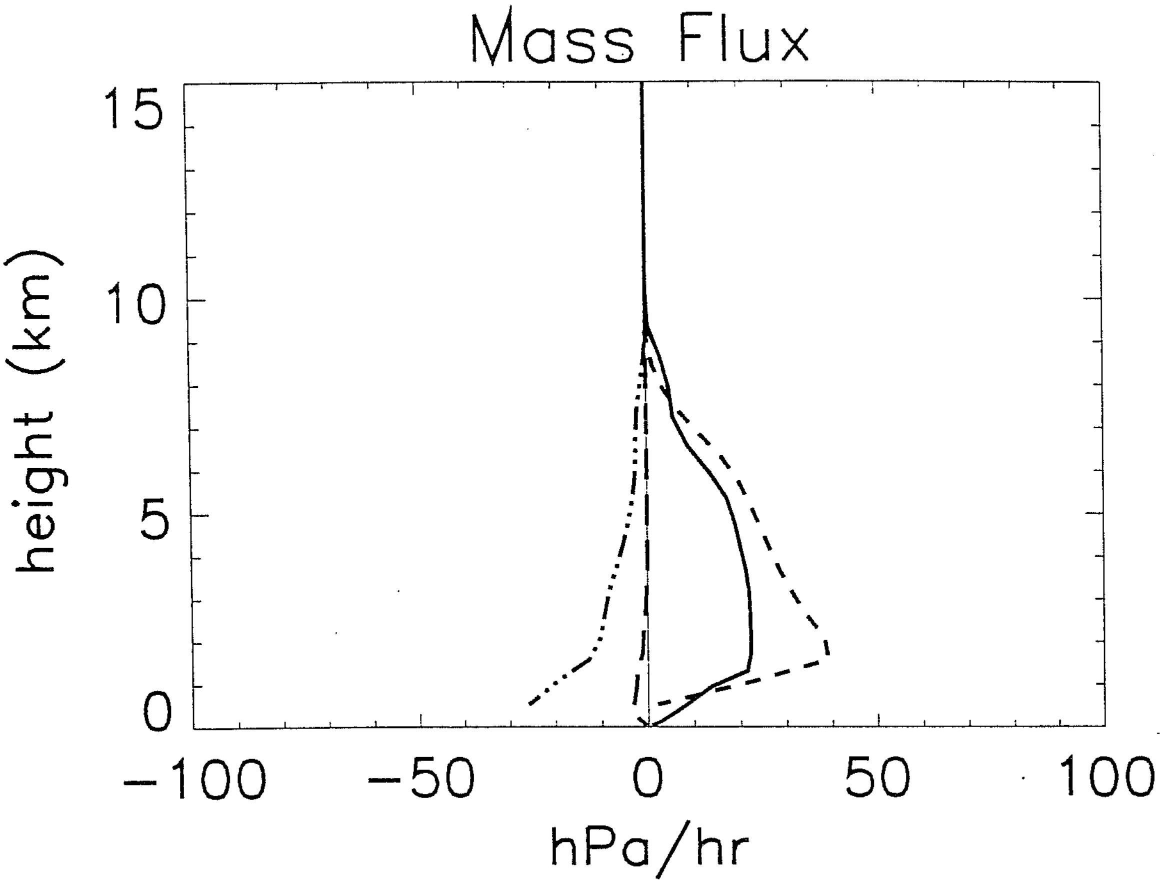

Figure 1 Mass fluxes for the CRM (UD : short dash, DD : triple dot dash) and SCM (UD : solid, DD : long dash) for simulation 232 and experiment E32 (10 hour averages)

CRM, being 1-2m/s slower than that of the large-scale. At 9km the parametrized updraughts horizontal wind is near the large-scale value, a consequence of the *enhanced* entrainment/detrainment rates used in equation (4) to represent the effects of cloud pressure gradients being unity, implying that the horizontal momentum of the updraught is totally mixed with the cloud environment. Also shown in figure 2a is the parametrized updraught horizontal wind from a parallel SCM experiment in which entrainment/detrainment rates are not enhanced in the cloud momentum equation (experiment E32ncpg), i.e. ignoring the effects of the cloud pressure gradients. Much larger differences in velocity exist between the updraught and the cloud environment illustrating, as in GKI97, the important influence of the cloud scale pressure gradients.

The net impact of convection (Q3) for experiment E32 is shown in figure 3 compared with that from the CRM simulation. The parametrization well reproduces the CRM results, with westerly acceleration of the flow in the lower troposphere and deceleration of the flow in the upper part of the cloud layer. The updraught contribution is dominant, downdraughts only providing a small contribution in the lowest 2km where they decelerate the westerly flow between 1 and 2km, and accelerate the flow below this height. The structure of Q3 implies that the momentum transports by convection are inherently

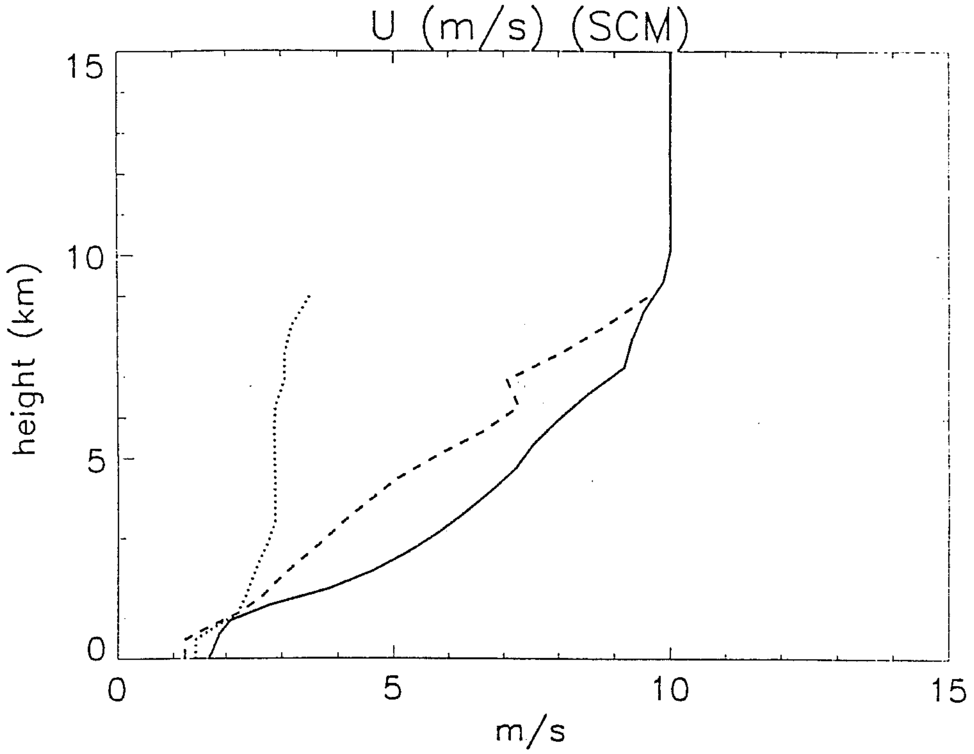

Figure 2a Large-scale (solid) and updraught (dash) zonal wind from the SCM experiment E32 (10 hour averages). Also (dotted) updraught zonal wind for experiment E32ncpg, with effects of cloud pressure gradients on updraught horizontal wind neglected.

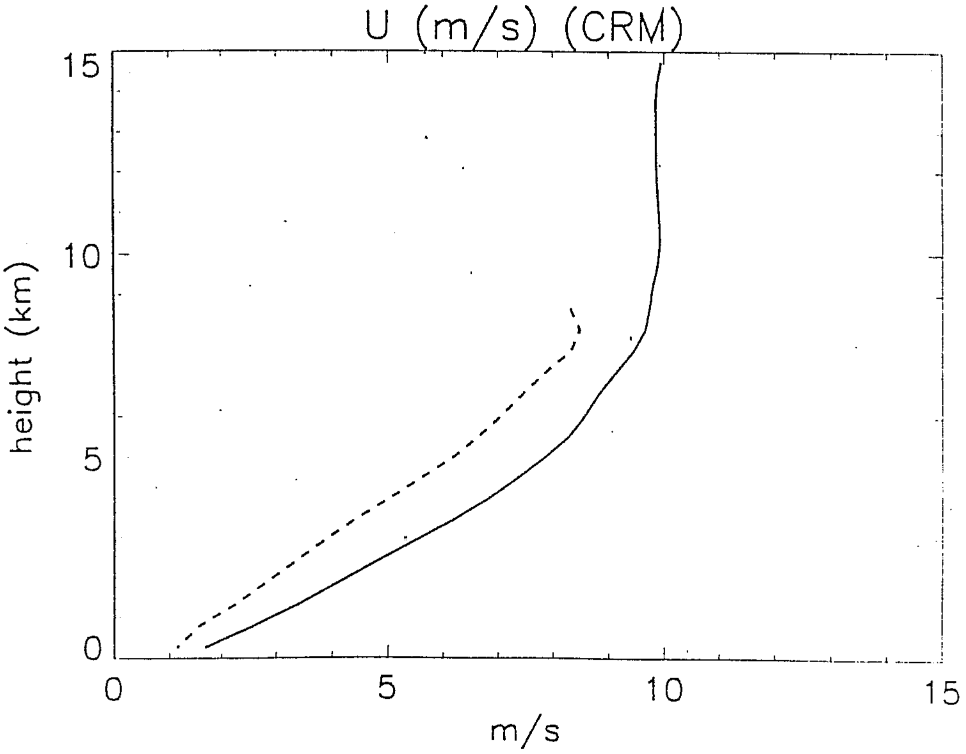

Figure 2b As figure 2a but for CRM simulation 232 (10 hour average)

downgradient in nature, as might be expected for unorganised convection. Also shown in figure 3 is Q3 from experiment E32ncpg. As shown previously ignoring the effects of cloud pressure gradients upon the updraught horizontal momentum gives rise to a larger differential between the updraught and large-scale wind fields, so overestimating the vertical flux of momentum by convection and consequently Q3.

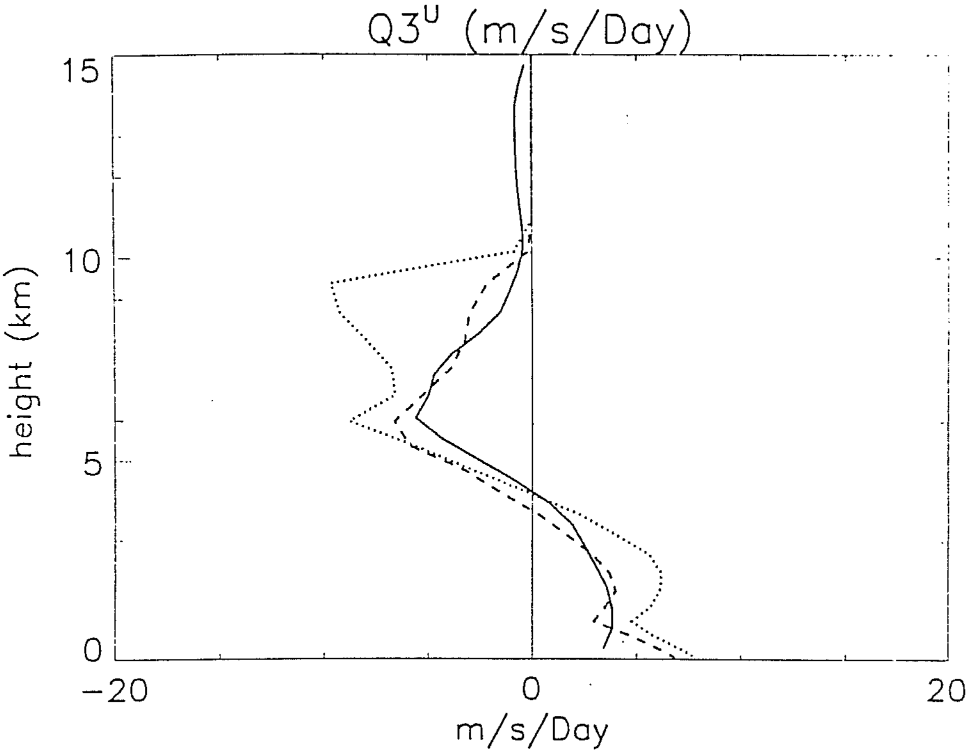

Figure 3 Q3 from CRM simulation 232 (solid) and SCM simulations E32 (dashed) and E32ncpg (dotted) (10 hour averages).

Further experiments were carried out to test the robustness of the parametrizations performance to changes in convective intensity and magnitude of the shear. In experiment E36 (comparable to CRM simulation 236) the surface latent heat flux is doubled, roughly doubling the updraught mass flux (and surface precipitation), while in experiment E37 (comparable to CRM simulation 237) both the surface latent heat flux and shear over the lowest 6km is doubled (from 10 to 20m/s). Gregory et al (1997) found that the magnitude of the pressure gradient term varies linearly with both mass flux and shear, the maximum value being twice as large in CRM simulation 236, and four times as large in simulation 237 as in simulation 232. The formulation of the pressure gradient term used in the ECMWF convection scheme also has a similar variation with mass flux and shear. As is seen in figures 4a (E36) and 4b (E37), the parametrization well captures the variation in the magnitude of Q3 for these cases.

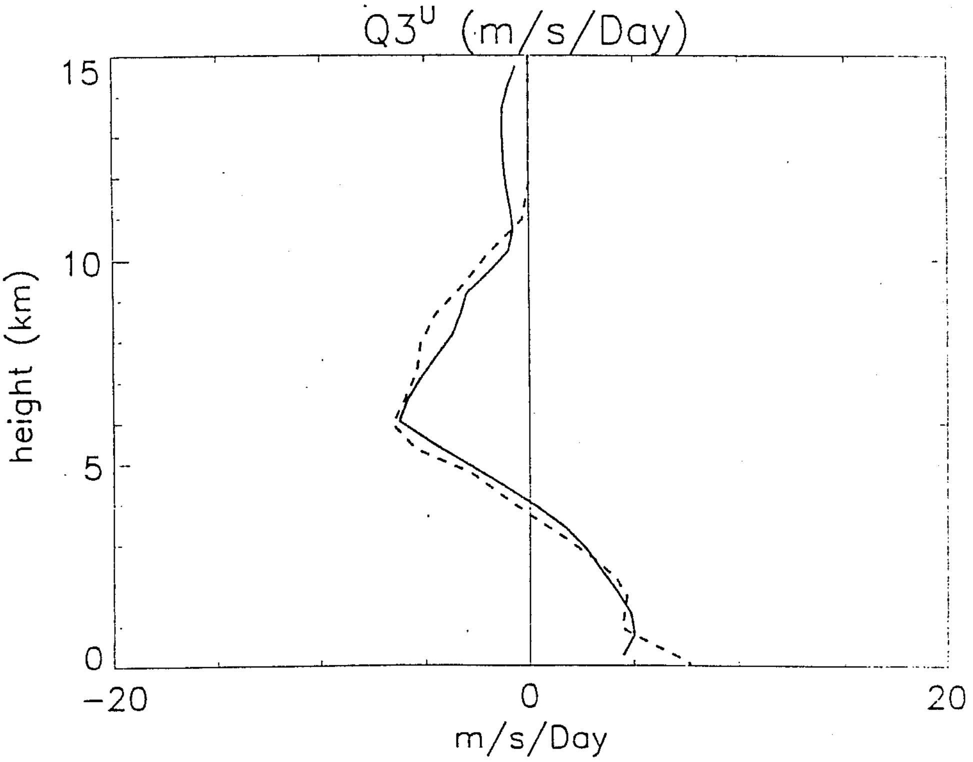

Figure 4a As figure 3 but for CRM simulation 236 and SCM experiment E36 (10 hour averages).

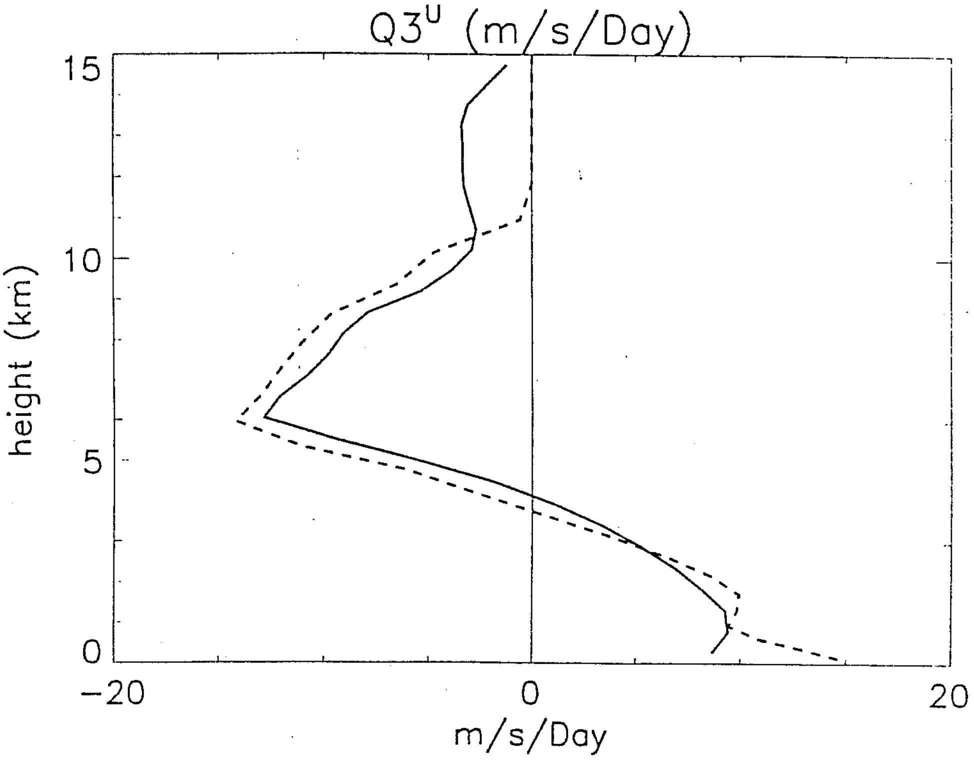

Figure 4b As figure 3 but for CRM simulation 237 and SCM experiment E37 (10 hour averages).

3.5 GATE simulation

The GATE case provides a very different wind regime in which to test the parametrization, with wind increasing and decreasing with height due to the presence of a low level jet in the lowest 6km of the initial wind profile. Such jet structures are often associated with the development of a squall lines but in the three-dimensional CRM simulations used here the cloud systems did not exhibit squall line type behaviour and were essentially unorganised. The updraught mass flux profile predicted by the convection scheme agrees well with that from the CRM above 5km, but is underestimated below this height (figure 5). This is a consequence of the weak downdraught in the lower troposphere. The net mass flux (not shown) predicted by the scheme is constrained to be in agreement with that of the CRM by the imposed large-scale cooling and moistening tendency (due to large-scale processes) which is the same in both SCM and CRM simulations. Hence if the downdraught mass flux is weak (together with the associated cooling effect), the updraught mass flux must reduce to allow the convection to balance the forcing.

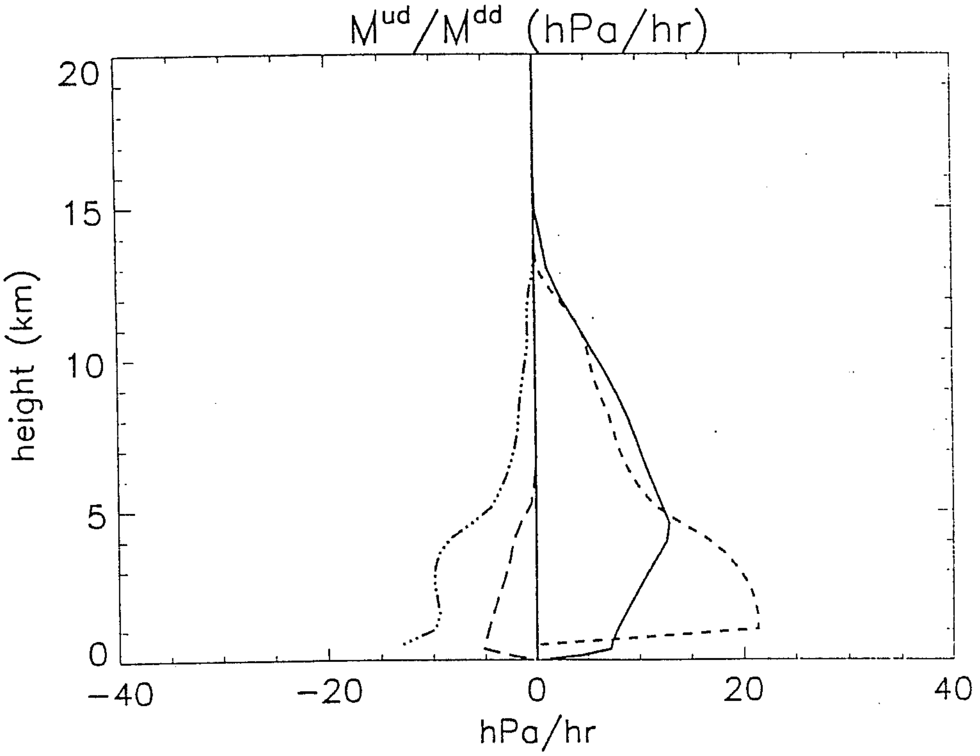

Figure 5 As for figure 1 but for CRM simulation 235 and SCM experiment E35 (10 hour averages)

The vertical variation of the updraught horizontal wind is similar to that seen in the CRM, being slower than the large-scale value below 4km and faster above this (figure 6a,b). Below the maximum in the updraught horizontal wind the values are lower than in the CRM but higher above, implying

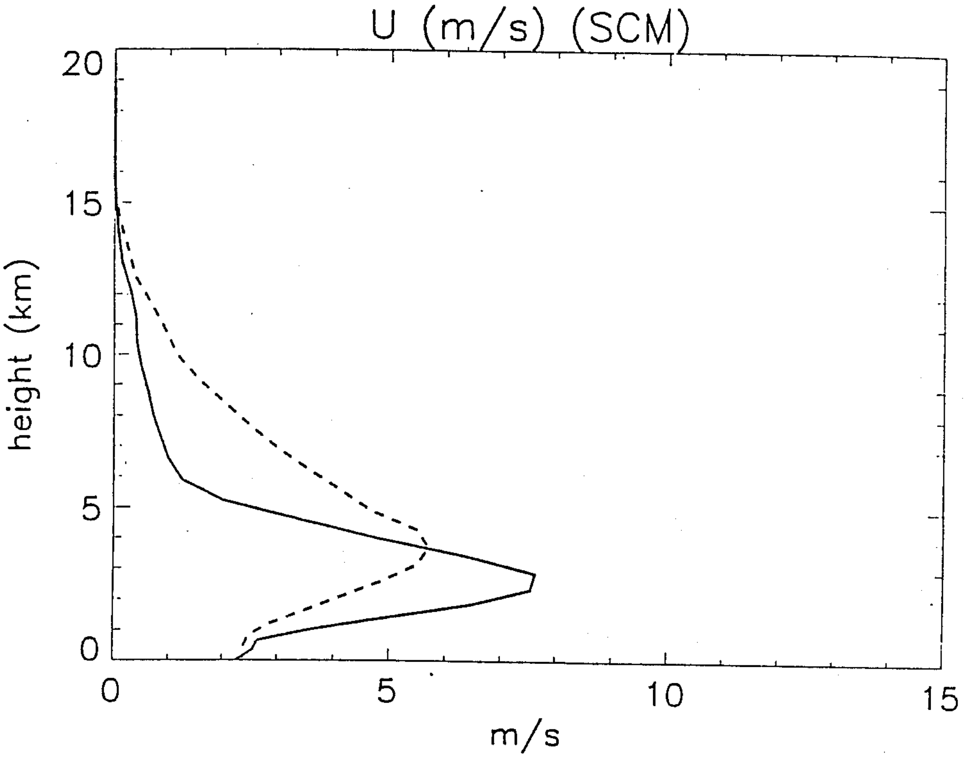

Figure 6a Large-scale (solid) and updraught (dash) zonal wind from the SCM experiment E35 (10 hour averages).

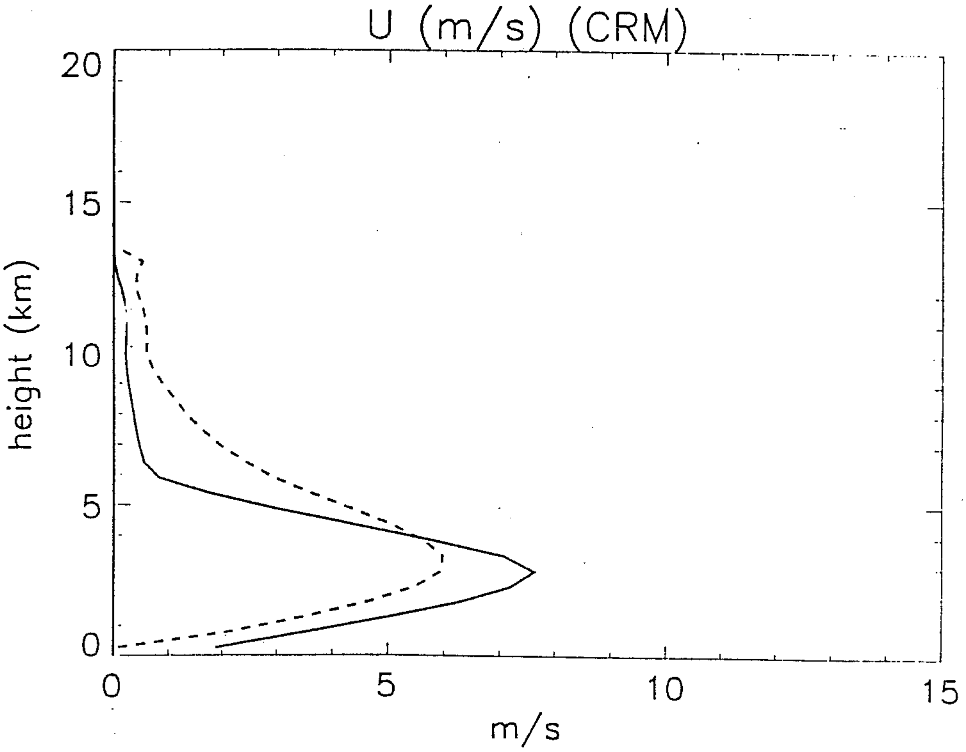

Figure 6b As figure 6a but for CRM simulation 235 (10 hour averages).

that the effects of horizontal mixing and cloud pressure gradients within the parametrization are weaker than in the CRM simulation. The larger difference in wind speed in the vicinity of the low level jet is compensated for the lower mass flux and the Q3 (figure 7) predicted by the parametrization agrees well with that of the CRM below 5km. Above this height, as the horizontal wind within the updraught is greater than that in the CRM while the mass fluxes are similar Q3 is over predicted. Again, away from the surface and the top of the convecting layer, the convective momentum transports can be viewed as downgradient with momentum being removed from the jet core and the flow above and below this level being accelerated.

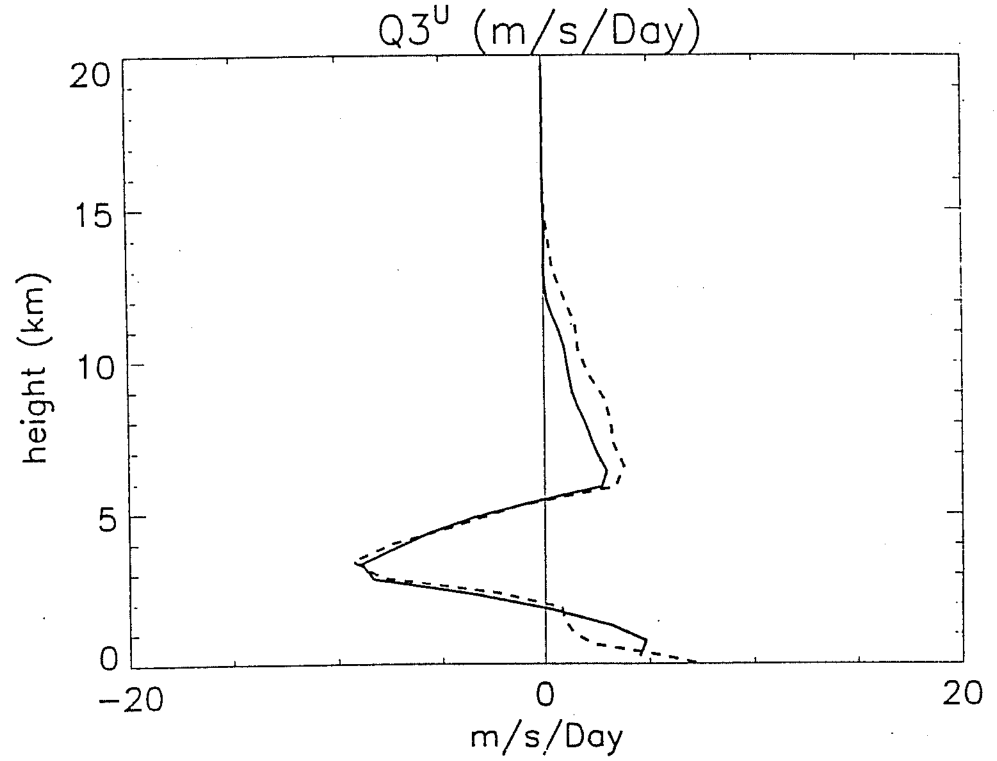

Figure 7 Q3 from CRM simulation 235 (solid) and SCM simulation E35 (dashed) (10 hour averages).

4. IMPACT OF CONVECTIVE MOMENTUM TRANSPORT UPON MODEL CLIMATE

Recent studies by *Zhang and MacFarlane* (1995), GKI97 and *Inness and Gregory* (1997) have documented the impact of the inclusion of convective momentum transports upon the climatology of the Canadian Climate Model and UK Met. Office Unified Model (in its climate configuration). Tropical systematic zonal wind errors were found to be reduced while the Hadley circulation was intensified. In the case of the Unified model the variance of outgoing long wave radiation (OLR) in the tropics was reduced, indicating synoptic variability had decreased. *Inness and Gregory* (1997) also note changes in the mean December/January/February precipitation pattern, with precipitation increasing along the ITCZ in the Pacific north of the equator and reducing along the SPCZ. These changes appeared to be associated with a weaker response of the Unified Models diabatic processes to the annual cycle of solar radiation.

The impact of convective momentum transports upon the ECMWF model is somewhat similar to that seen in these previous studies. Figure 8 shows the difference between simulated and ECMWF re-analysis (ERA) zonal mean winds for December/January/February 1987/88 for simulations with (ZL1X) and without (ZL8P) convective momentum transports. Both simulations were carried out using CY14R3 of the ECMWF model at T63 horizontal resolution with 31 levels in the vertical. The simulations started from the 1st of November 1987. Wind errors in the control simulation (without convective momentum transports - fig 8a) show an easterly bias through much of the tropical troposphere and sub-tropics, especially above 600mb (level 20). Inclusion of convective momentum transports reduces errors below 100mb (level5) and at lower levels in the sub-tropire introduced. This is mainly due to reduced easterly winds in the upper levels of the tropics across the west Pacific and Indian ocean. Meridional winds are also changed with the inclusion of convective momentum transports (not shown), the maximum zonal mean meridional wind in the upper level outflow of the Hadley circulation (at 10N, 200hPa) increasing from 2.1 to 2.6m/s. This "spin-up" of the zonal mean divergent circulation is associated with an intensification of precipitation over the warm pool of the central Pacific and in the SPCZ (figure 9), improving the simulation of precipitation compared with GPCP estimates. Rainfall is seen to decrease over the southern Indian Ocean when the effects of convective momentum transports are considered but is still underestimated over the Indonesian region.

Gregory et al (1997) noted tropical variability is affected by the inclusion of convective momentum transports. Earlier studies (Miller, personal communication) indicated that the frequency of spurious tropical cyclones was reduced when convective momentum transports were included into the ECMWF model. Figure 10 shows the mean standard deviation of 850hPa relative vorticity for December/January/February 1987/88 from ERA with experiments with and without convective momentum transports. The generally higher levels of variability in the ERA data reflect the higher resolution of the model (T106) used in the analysis procedure. When convective momentum transports are included, reductions in variability are found along the Pacific ITCZ east of the dateline and southern Indian Ocean. In the Pacific ITCZ simulated variability is closer to values found in the ERA data. Over the Indian Ocean comparison is more difficult as precipitation rates are greater than observed, especially when convective momentum transports are neglected. However as the model used has a resolution lower than that used in the re-analysis the magnitude of the variability simulated over

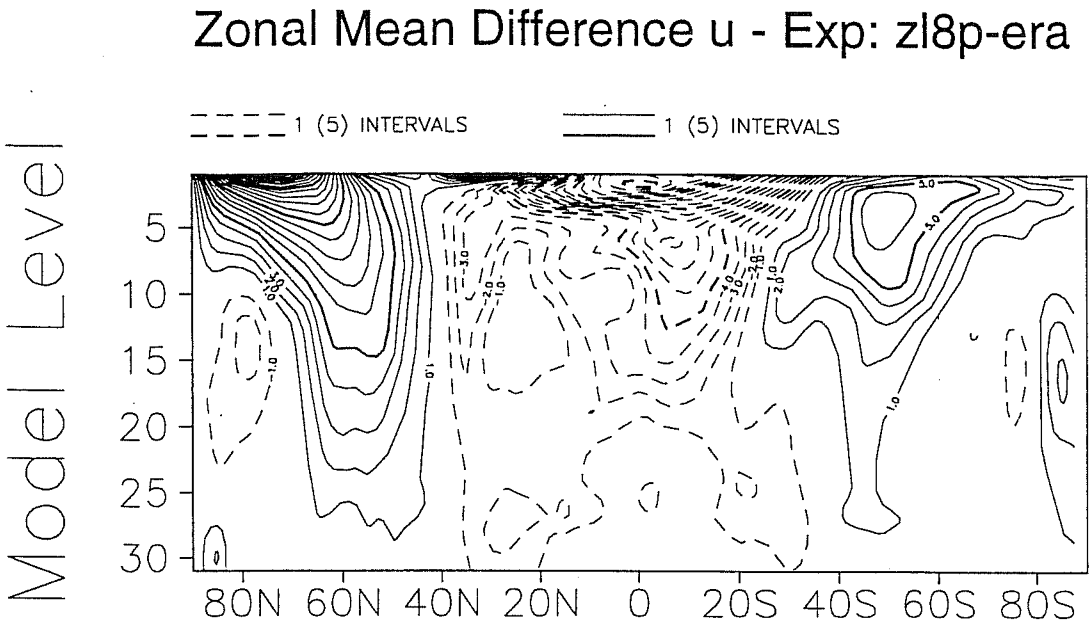

Figure 8a Difference in zonal mean wind between simulation ZL8P (without convective momentum transports) and ERA for December/January/February 1987/88.

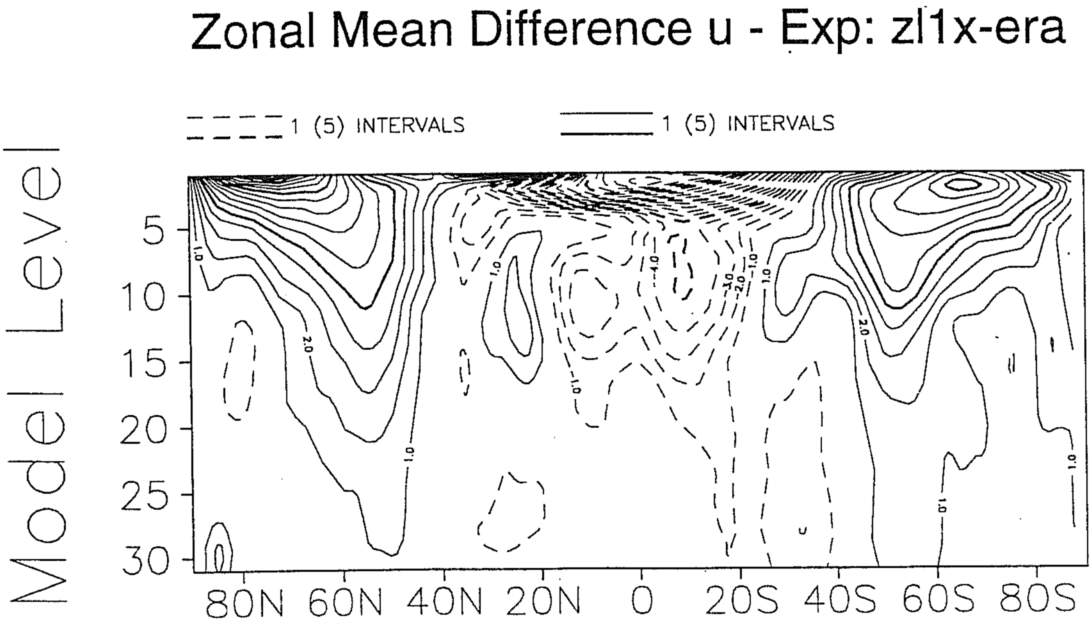

Figure 8b Difference in zonal mean wind between simulation ZL1X (with convective momentum transports) and ERA for December/January/February 1987/88.

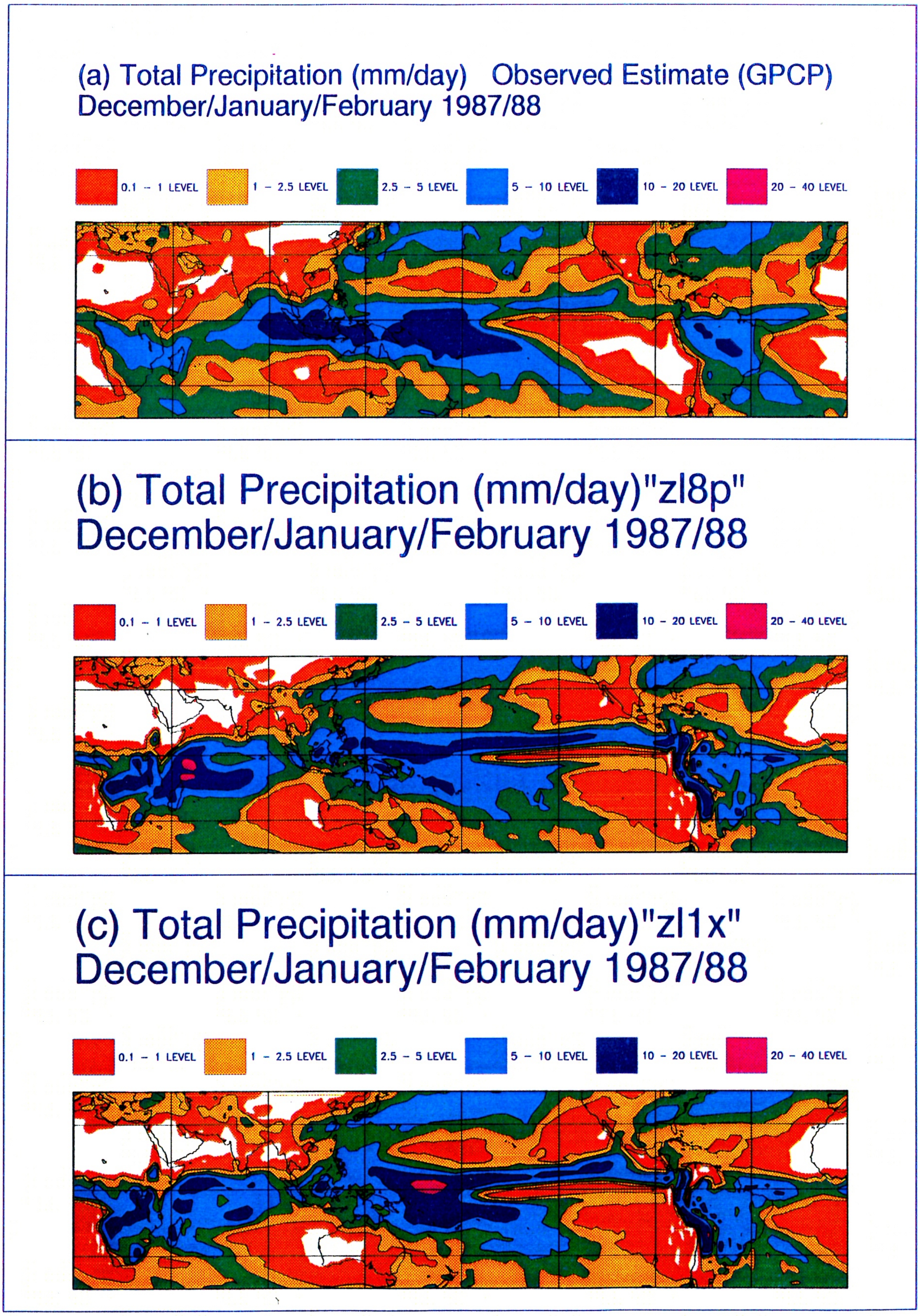

Figure 9 Total precipitation for December/January/February 1987/88 from (a) GPCP estimate, (b) simulation ZL8P without convective momentum transports and (c) simulation ZL1X with convective momentum transports. Both simulations started from the 1st of November 1987.

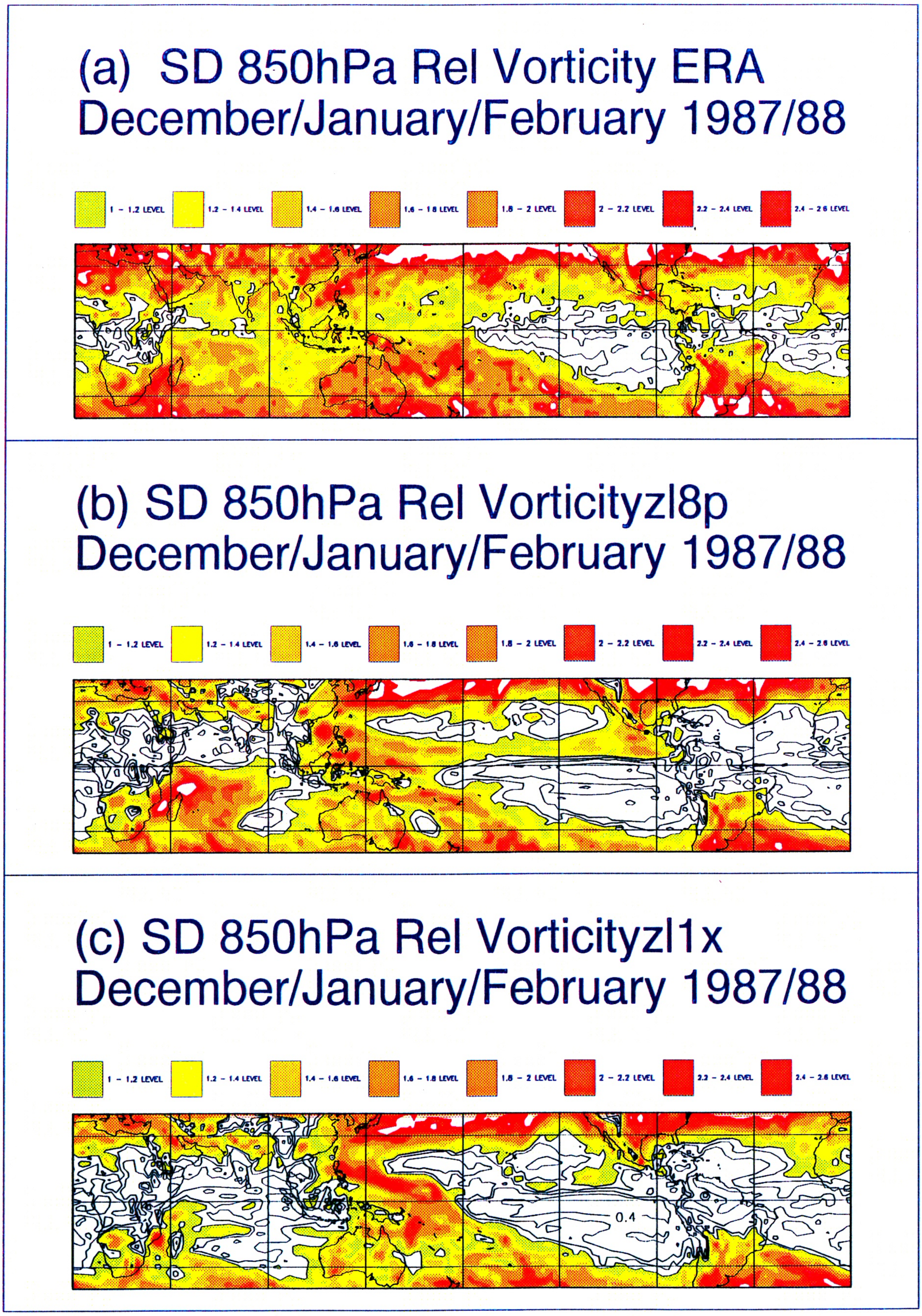

Figure 10 Standard deviation of 850hPa relative vorticity for December/January/February 1987/88 from (a) ERA, (b) simulation ZL8P without convective momentum transports and (c) simulation ZL1X with convective momentum transports. Both simulations started from the 1st of November 1987.

the Indian Ocean without convective momentum transports may be thought to be excessive and those in simulation ZL1X to be more realistic.

Over the west Pacific both simulation over estimate the level of variability, the linear structure being associated with spurious band of precipitation to the north of New Guinea and extending towards the Philippines. This increase in variability to the west of the date line with a reduction along the ITCZ in the east Pacific was also noted by GKI97 (as measured by a three year mean standard deviation of OLR). Excessive precipitation rates were also seen during DJF north of the equator in the west Pacific. They suggested that variability in this region may be enhanced when convective momentum transports are included due to weaker vertical shear favouring the formation of tropical depressions. If true then momentum transports associated with organised convection (tending to increase vertical shear) act to counter this. However this needs further study; other processes and factors, such as the frequency of cold air out breaks over the South China Sea, may also play a role in determining convective activity in the west Pacific north of the equator during DJF. Deficiencies in the model's representation of these may also contribute to model errors.

5. FURTHER DISCUSSION

This paper has attempted to demonstrate the utility of data provided by CRM simulations for the evaluation and development of convection schemes. Data provided from the UKMO CRM in two different convective regimes indicates that the convective momentum transports predicted by a revised version of the ECMWF convection scheme are reasonable for unorganised convection. The importance of including the effects of cloud scale pressure gradients has been noted. Although the formulation used to do this in the ECMWF convection scheme is simpler than the one proposed by GKI97 for use in the UK Met. Office Unified Model and has little theoretical basis, it appears to provide a reasonably realistic representation of the effects of cloud pressure gradients for different convective intensities and vertical wind shears. Use of the convective momentum transport parametrization in the ECMWF forecast model reduces wind errors in the tropical troposphere and tropical variability through much of the tropics.

Apart from how the effects of horizontal pressure gradients are to be included in convective momentum transport parametrizations, a further uncertainty to date has been the impact of convective organisation. The cases considered here were ones where the convection was unorganised and acted to reduce the vertical shear of the horizontal wind. However some types of organised convection, for example squall lines over Africa and the eastern tropical Atlantic are known to produce vertical momentum transports which enhance the vertical shear, i.e. up gradient transports. As noted above such organised systems develop in the presence of low level jets, as in the GATE case above, and in the presence of a westerly jet as here would accelerate the large-scale flow in the upper troposphere to the west rather than to the east as in figure 7 (see *Le Mone*, 1983, for example). For this to occur the vertical momentum flux due to convection must be negative in the upper troposphere, ie the in-updraught horizontal wind must be easterly (negative) while the large-scale wind be westerly, or easterly but slower than the in-cloud value. This is achieved by large across cloud pressure gradients which provide an easterly acceleration to the updraught air. However representing the cloud pressure gradients by enhanced horizontal mixing with the large-scale environment (as in the ECMWF scheme) implies that the in-cloud wind can only be adjusted back to the large-scale value. Thus with an initial wind profile which is westerly the in-cloud wind profile cannot become easterly and so momentum transports remain downgradient.

Wu and Yanai (1994) discussed the parametrization of convective momentum transports associated with meso-scale convective systems over the central USA, including the impact of organization. They used the theoretical analysis of *Rotunno and Klemp* (1984), which for symmetrical clouds predicts a form for the pressure gradient term similar to that suggested by GKI97, to represent cloud systems which are strongly asymmetrical, e.g. a quasi two-dimensional squall line. However their results were inconclusive and an effective method to represent the effects of organization is not yet available.

The question as to the importance of the effects of organisation upon convective momentum transports remains to be answered. As seen above the use of a representation of the effects of unorganised convection upon horizontal momentum (reduction of shear) tends to reduce model systematic wind errors in the tropics, while the nature of transports associated with organised convection (enhancing shear) would tend to exacerbate errors. However such organised transports may be important in specific regions, for example in the Sahel region where long lives squall lines form in the vicinity of a low level jet in association with easterly waves. Such squall lines also occur in other regions, such as the west Pacific, but have a tendency to be more transitory. Recent CRM simulations of these short lived systems (Redelsperger, personal communication) suggest that the momentum transports associated with them tend to reduce vertical shear in contrast to those of long lived squall lines over Africa and the eastern tropical Atlantic. It is clear that further work utilising CRM studies, combined with SCM and GCM modelling, will be useful in clarifying these uncertainties.

6. ACKNOWLEDGEMENTS

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