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**Changes and developments to Convective Momentum Transport (CMT)
parametrization based on analysis of CRM and SCM.**



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Changes and development to Convective Momentum Transport (CMT) parametrization based on analysis of CRM and SCM.

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Abstract

Cloud resolving model (CRM) simulations of deep convection are used to analyse the transport of momentum in the presence of deep convection. These simulations are analysed using mass flux and turbulence ideas to reexamine the basis of Gregory-Kershaw CMT parametrization and the current turbulence based CMT scheme. The analysis shows why the current CMT scheme may be too strong at high levels. A new improved turbulence scheme is developed. All the deep CMT schemes are tested in the single column model (SCM) and results compared with the CRM simulations. Both the new turbulence scheme and the Gregory-Kershaw scheme are better than the old turbulence based scheme. Climate and NWP tests of the schemes are unable to show a clear winner between the new turbulence scheme and the Gregory-Kershaw scheme. Areas for future work are identified, including CMT over orography.

1 Introduction

1.1 Why the need to look at CMT now?

Numerical Weather Prediction (NWP) forecast tests for the 70 level project exposed problems with tropical winds at upper levels ($\sim 200hPa$). The winds tend to be too slow suggesting that the current deep convective momentum transport (CMT) scheme could be too strong at upper levels. The immediate problem was overcome by tuning, (referred to later as the shape tuning), the existing deep CMT scheme to reduce its impact at upper levels but this was done without any physical evidence that this was the right approach.

NWP forecasts also sometimes show problems with winds over steep orography. These problems have been traced to large CMT increments coming from mid-level CMT. An alternative diffusive mid-level CMT scheme is described (section 4) and tested, section 6.3, to see whether this has any impact.

1.2 What CMT parametrization does the UM currently use?

The Unified Model (UM) currently uses a turbulence based convective momentum transport scheme developed by A Grant (Gregory et al, 2005) for shallow and deep convection and the Gregory-Kershaw CMT scheme for mid-level convection (Gregory et al 1997, Kershaw & Gregory 1997). The turbulence CMT scheme was introduced into the UM

at the same time as the new dynamics. The documentation available about the scheme implies it was based on CRM simulations of shallow convection and was extended to deep convection without extra any CRM modelling. The aim of this report is to use CRM simulations of deep convection to investigate the ideas behind the deep turbulence scheme, improve it and assess how well it performs against the Gregory-Kershaw scheme for deep convection.

1.3 What is done elsewhere?

The importance of including convective momentum transports in both NWP and climate models to help model the general circulation of the atmosphere is now widely accepted.

Looking back the observation study of the magnitude of momentum transported by cumuli by Houze (1973) showed that CMT could be of similar in magnitude to other terms in the momentum budget. Stephens (1979) analysing the momentum budget of GATE easterly-wave data attributed residuals in the budget to convective activity. LeMone (1983) demonstrated that cloud pressure gradients are important in determining the winds inside clouds.

The earliest attempts to parametrize convective momentum e.g. Schneider & Lindzen (1976) assumed that the momentum inside a cloud was only affected by lateral entrainment of environmental momentum from outside the cloud. Later Zhang and Cho (1991a,b) included the effect of cloud pressure gradients by using a simple model of flow around a cloud. This scheme was shown (Zhang and McFarlane 1995) to have a beneficial impact when use in the Canadian Community Climate model, increasing the Hadley Circulation by reducing the vertical wind shear. Wu and Yanai (1994) and Kershaw and Gregory (1997) both parametrized the cloud pressure gradients in terms of the convective mass flux and large-scale vertical wind shear. ECMWF uses a form of the Gregory-Kershaw scheme modified to work with the Tiedtke (1993) convection scheme.

Momentum budget analyses of reanalysis data to find residuals (Lin et al, 2008) have been used to show how large the impact of CMT may be and how important it is to the general atmospheric circulation. Carr and Bretherton (2001) have compared residuals from reanalyses with the Schneider & Lindzen(1976) and the Gregory-Kershaw (1997) CMT parametrization showing the Gregory-Kershaw scheme does well above 850hPa. Below 850hPa they suggest the CMT schemes don't do so well in areas of shallow convection. Note the UM now uses a turbulence based scheme for shallow CMT.

The Unified Model's mass flux convection scheme does not attempt to model organised convective systems. Similarly the CMT parametrization does not model the influence of organised meso-scale convective systems on momentum transport. Observations (LeMone 1983, Hogan et al 2008) and mesoscale modelling studies of organised convective systems (Mechem et al 2006) suggest that the momentum transport in such systems may be different, in some cases the organisation of the convection can result in wind shear being increased by the presence of a convective system. Gray (2000) modelling a MCS using a CRM finds that momentum transport by mesoscale updraughts is negligible relative to the transport by convective updraughts, but momentum transport by meso-scale precipitating downdraughts is of similar magnitude to convective downdraughts and is counter gradient. Zhang & Wu (2003) using a 2d CRM find that during westerly wind bursts the momentum transport is counter gradient. Moncrieff and Klinker (1997) studying ECMWF model output looking at the TOGA COARE period found evidence that during periods of strong westerly winds when organised convection occurs the model over predicts the vertical

transport of momentum as it does not fully resolve such systems.

So far there is no published systematic global study showing whether the neglect of parametrizing the CMT of organised systems has any significant impact on the global circulation errors of a GCM. A study of T+24 hour wind errors by P Bechtold (personnel communication) found errors grow with time but in cases of westerly wind bursts (i.e. convection is more likely to be strongly organised), there are big errors due to CMT increments being of the wrong sign. Studies like Carr & Bretherton (2001), using reanalysis residuals and comparing these with the Gregory-Kershaw parametrization of CMT find good agreement above 850hPa supporting the idea that most convection results in down gradient transport of momentum.

1.4 What has this study looked at?

This study concentrates on looking at convective momentum transport by deep convection. Section 2 describes the cloud resolving model (CRM) simulations of deep convection used to analyse momentum transport in deep convective clouds. The CRM simulations are used to assess both the Gregory-Kershaw scheme (Kershaw & Gregory, Gregory et al, 1997) and the current model CMT parametrization, and look at ways to improve them. The different CMT parametrization schemes are tested in the UM single column model for the same cases as the CRM simulations (section 3). Section 4 describes an alternative parametrization of CMT for use with mid-level convection. Section 5 discusses the problems in the UM of doing CMT over orography. The results from testing the schemes in climate mode are given in section 6 and in NWP mode in section 7.

2 CRM simulations of deep convection and their analysis

The Met Office cloud resolving model (Petch 2006) was used for a series of simulations to investigate the impact of convection on winds. Table 1 gives a list of the cloud resolving model simulations run. The simulations chosen are based on those used by Kershaw and Gregory (1997). In all simulations the Coriolis force was turned off. The winds were allowed to freely evolve from an imposed initial profile. The evolution of the wind profile was assumed to be due mainly to the impact of the presence of convection and not due to the presence of any gravity waves. Making these assumptions it is possible to analyse the momentum budget of the simulations and determine the impact of convection on the winds.

All cold air outbreak simulations were run for 10 hours allowing the winds to freely evolve from their initial profiles. The simulation r6121 was started from a previous simulation with fully developed deep convection but no winds. The required wind profile was imposed by relaxation for 4 hours and then allowed to freely evolve for another 10 hours. The tropical GATE simulations were run for 12 hours; the winds were relaxed back to the required profiles for the first 2 hours to allow some convection to develop and then allowed to freely evolve.

All the CRM simulations apart from r6121 (with 15 minute output) were set up to output hourly mean and instantaneous data. This hourly data has been used for analysis of the runs.

Table CRM simulations

CRM simulation	Domain (kmxkm)	Horizontal resolu- tion (m)	Vertical resolution	Latent and sensible heat (Wm ⁻²)	Initial wind profile (m/s)
r1002 cold air outbreak	32x32	250	80 levels 15km top 25 levels below 1km	400.0, 100.0	u=0.0, v=10.0 at 6km
r1003 cold air outbreak	32x32	250	80 levels 15km top 25 levels below 1km	400.0, 100.0	u=0.0, v=20.0 at 6km
r1004 cold air outbreak	32x32	250	80 levels 15km top 25 levels below 1km	800.0, 100.0	u=0.0, v=10.0 at 6km
r1005 cold air outbreak	32x32	250	80 levels 15km top 25 levels below 1km	200.0, 100.0	u=0.0, v=10.0 at 6km
r1006 cold air outbreak	32x32	250	80 levels 15km top 25 levels below 1km	400.0, 100.0	u=16.0, v=12.0 at 6km
r6121 tropical (TOGA COARE like)	64x64	500	80 levels, 20km top, 14 levels below 1km	w forcing	jet below 6km, u=10.0, v=0.0
r2003 GATE tropical case	64x64	500	80 levels, 20km top, 14 levels below 1km	145.0, 12.0	jet below 6km u=10.0, v=0.0
r2004 GATE tropical case	64x64	500	80 levels, 20km top, 14 levels below 1km	145.0, 12.0	Wind in- creasing with height, speed=10.0 at 20km

2.1 General analysis

For the CRM simulations described above the horizontal momentum budget is given by

$$\frac{\partial (\rho \bar{u})}{\partial t} = - \frac{\partial (\rho \overline{u'w'})}{\partial z} \quad (1)$$

where u and w are the zonal and vertical components of wind, ρ is the air density, z the

height above the surface and t time. The overbar denotes an average over the horizontal domain of the simulation. Primes indicate departures from the horizontal domain mean value. If the air density is assumed to depend purely on height then the change in the domain mean wind with time can be determined by working out the vertical gradient of the momentum flux. In the case of the CRM, air density does depend solely on height but this is not the case for the UM.

2.2 Analysis using methods of Kershaw and Gregory

This section uses our CRM simulations to repeat the analysis of Kershaw and Gregory (1997). Kershaw and Gregory (1997) took a mass flux approach partitioning the momentum flux into contributions from updraught, u , downdraught's, d and the environment, e .

$$\overline{\rho u' w'} = \sigma^u \overline{\rho u' w'^u} + \sigma^d \overline{\rho u' w'^d} + \sigma^e \overline{\rho u' w'^e} \quad (2)$$

where the primes indicate departures from the domain mean but the u , d , e indicate a mean over grid points classed as updraught, downdraughts or environment (neither).

They assumed contributions from the environment could be neglected.

Figures 1 and 2 show the environmental components as analysed from the CRM runs r1002 and r2003. In both cases if the updraughts are classed as all cloudy updraughts then the environmental flux is very small. If the updraughts are classed as only buoyant cloudy updraughts then the remaining environmental flux is not negligible. In the case of the cold air outbreak where the cloud top is around 8km there is still a small non-negligible $w'w'$ flux above the cloud top. This is likely to be due to gravity waves.

For the updraught, $u' = u - \bar{u}$ so that;

$$\overline{\rho u' w'^u} = \overline{\rho(u - \bar{u}) w'} = \overline{\rho u w'^u} - \overline{\rho \bar{u} w'^u} \quad (3)$$

Within the updraught Kershaw & Gregory (1997) then took $u^* = u - \bar{u}$ giving

$$\overline{\rho u' w'^u} = \overline{\rho u^* w'^u} - \overline{\rho \bar{u} w'^u} + \overline{\rho u^* w'^u} \quad (4)$$

Assuming the intra-updraught correlations between u and w are small the last term on the right hand side can be neglected:

$$\overline{\rho u' w'^u} = \rho (\bar{u}^u - \bar{u}) \overline{w'^u} \quad (5)$$

Using the same approach for the downdraught term gives the following approximation for the momentum flux.

$$\overline{\rho u' w'} = \sigma^u \rho (\bar{u}^u - \bar{u}) \overline{w'^u} + \sigma^d \rho (\bar{u}^d - \bar{u}) \overline{w'^d} = m^u (\bar{u}^u - \bar{u}) + m^d (\bar{u}^d - \bar{u}) \quad (6)$$

where m is the mass flux.

Figures 1 and 2 show that the mass flux approximation whether for all (d) cloud updraughts or (e) only buoyant cloud updraughts is not a perfect fit to the updraught momentum flux. In both cases the approximation tends to under estimate momentum flux higher in the cloud.

Figures 1(f) and 2(f) show that the downdraught momentum flux is small relative to the updraught flux. The mass flux approximation gives a good fit to the downdraught

Figure 1: Eight hour mean profiles of momentum stresses for r1002. (a) & (b) show the total stress profile, the downdraught profiles and for (a) the buoyant cloudy updraughts and environmental profile deduced from assuming buoyant cloud updraughts, (b) shows the same for all cloudy updraughts, (c) shows the environmental part of the stress plus the very small part due to turbulence, (d) shows the mass flux approximation for the updraughts versus the actual flux for buoyant cloudy updraughts, (e) the same for all cloudy updraughts, (f) the downdraught stress profile and the mass flux approximation to the downdraughts.

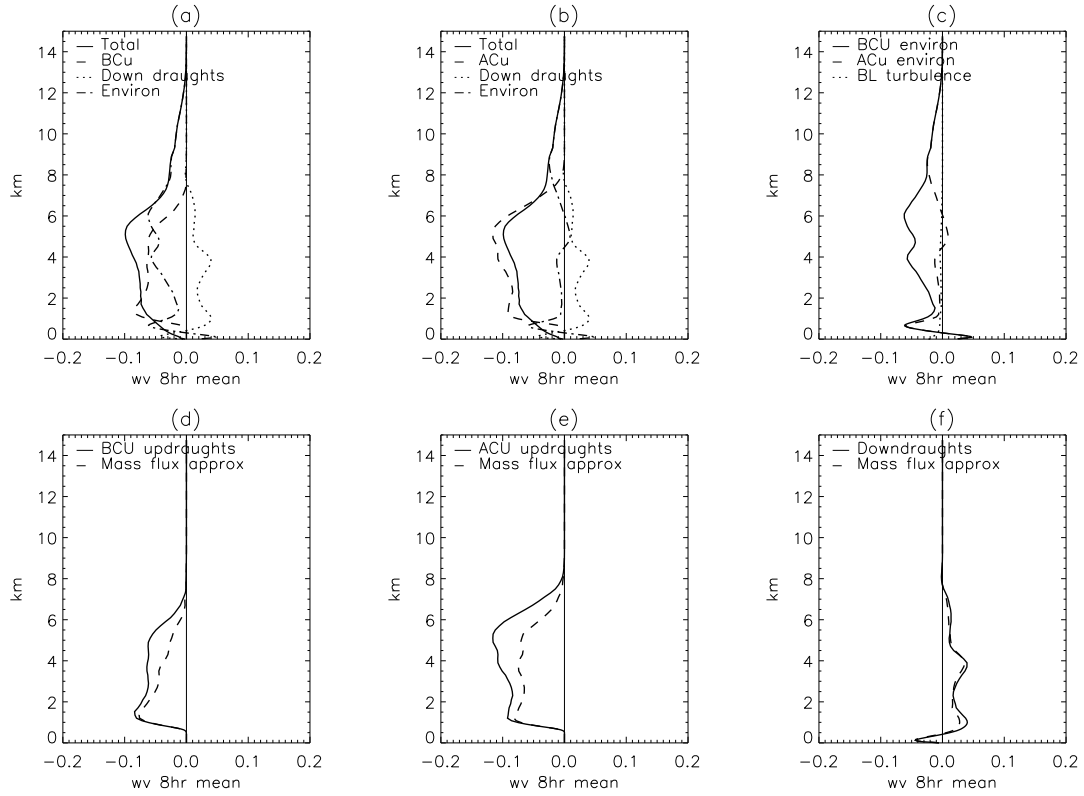
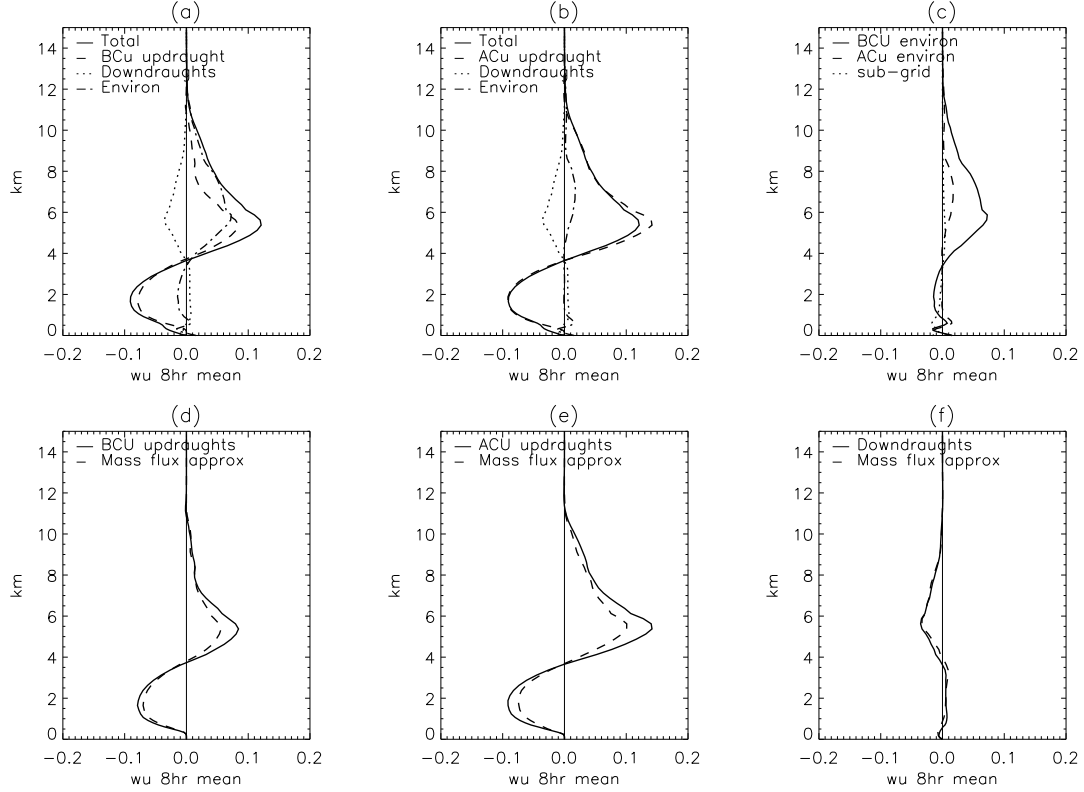


Figure 2: As for figure 1 but for 8 hour means profiles of momentum stress for r2003.



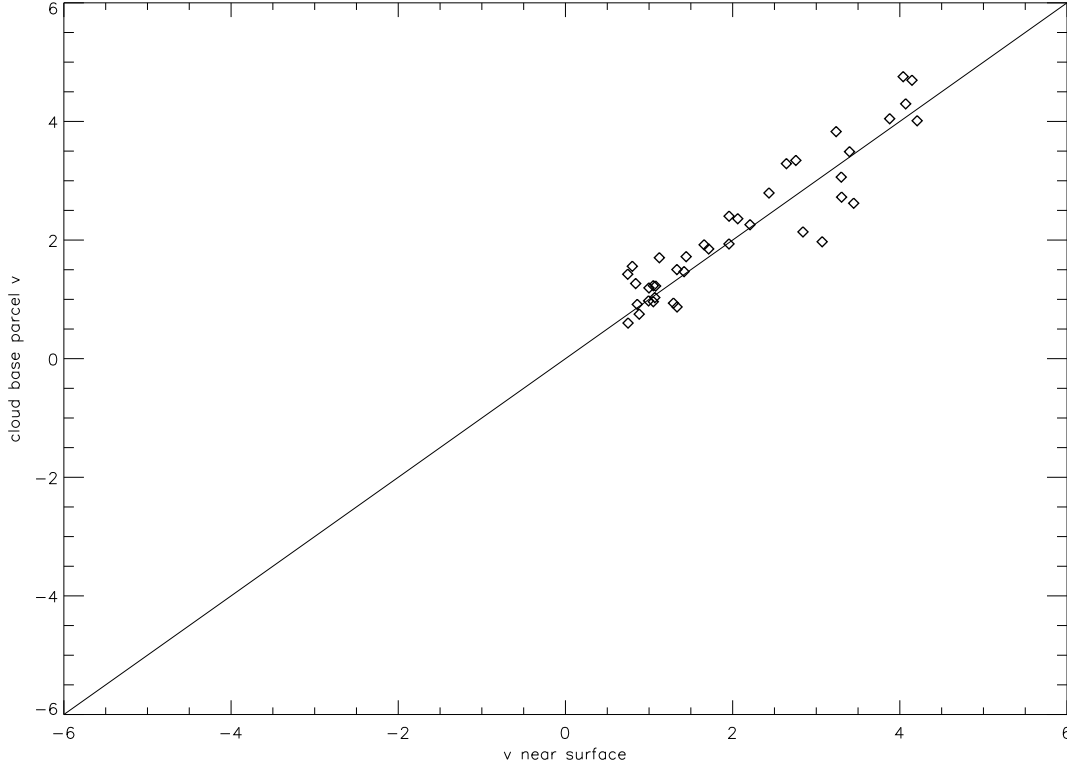
flux. The downdraught terms are small relative to the updraught terms so neglecting the downdraughts in a parametrization of convective momentum transport is possible. Neglecting the downdraughts will tend to cancel out some of the errors coming from making a mass flux approximation for the updraught fluxes for the simulations studied here.

2.2.1 Cloud-base closure for updraughts

To predict the updraught winds in the plume the values at cloud base are required. The original mass flux scheme of Kershaw and Gregory started from the near surface assuming the initial plume winds were equal to the environmental winds. The current mass flux convection scheme now works from cloud base rather than the near surface so requires a closure based on the plume winds at cloud base.

Figure 3 shows a plot of the CRM updraught winds at cloud base versus the CRM mean winds near the surface ($0.1z_{lcl}$, where z_{lcl} is the height of the lifting condensation level). This shows a very good fit, so the updraught winds at cloud base for the plume in the UM are now initialised to the environmental winds at the model level nearest to $0.1z_{lcl}$. This choice of closure allows the Gregory-Kershaw scheme to be used for deep convection with the current mass flux scheme. The mid-level version of the Gregory-Kershaw scheme still takes the initial plume winds as equal to the environmental winds at the level at which the mid-level convection starts.

Figure 3: Plot of near surface wind ($\sim 0.1z_{\text{cl}}$) against cloud-base parcel wind for all CRM simulations.



2.2.2 Neglect of downdraughts.

We have chosen to neglect the downdraught term in the UM, as this is small relative to the updraught term.

If the downdraught term is not neglected then a downdraught wind at the top of the downdraught plume is required for closure. Looking back at old UM code for UM4.5 shows that the downdraughts were initialised with the mean of the environmental wind and the value of the updraught wind for the layer. (This assumption has not been checked against CRM data.) The code to do CMT for downdraughts is no longer available in the UM.

2.2.3 Parametrization of parcel wind

From Gregory-Kershaw the wind in the updraught is given by

$$\frac{1}{\rho} \frac{\partial (\sigma^u \rho \overline{u^u w^u})}{\partial z} + D \overline{u^u} - E \overline{u} = -\frac{1}{\rho} \sigma^u \frac{\partial \overline{p^u}}{\partial x} \quad (7)$$

where D is detrainment and E entrainment. To calculate the updraught wind the pressure gradient term needs to be evaluated. Gregory-Kershaw found that the pressure gradient term could be parametrized by using

$$\frac{1}{\rho} \sigma^u \frac{\partial \overline{p^u}}{\partial x} = C^u m \frac{\partial u^E}{\partial z} \quad (8)$$

Their fit to CRM used a value for C^u of 0.7. Taking the pressure term directly from our deep simulations and comparing it with the gradient of the environmental wind multiplied by the buoyant cloudy mass flux, our deep simulations are consistent with this value of C^u . The cold air out break case giving a better fit to the CRM pressure term using the gradient wind than the Tropical jet case.

The success of the Gregory-Kershaw approach is dependent on how well the mass flux parametrization of the thermodynamics of the plume model the real entrainment, detrainment and mass flux.

2.3 Analysis using turbulence ideas.

This section analyses the same set of CRM simulations using turbulence ideas i.e. a non-local eddy diffusivity approach (Holtslag & Boville 1993, Lock et al 2000) usually used to model the sub-cloud layer of the cumulus boundary layer and applies them to the transport of momentum fluxes in deep convection. The turbulence approach assumes the momentum flux can be divided into a gradient term and a non-gradient term

$$\overline{\rho u'w'} = \overline{\rho u'w'}_{grad} + \overline{\rho u'w'}_{non-grad} \quad (9)$$

where u is the East West component of wind, w the vertical velocity and similar equations exist for v , the North South component of wind.

Grant (2003) suggested that the exact form of the gradient and non-gradient terms should be

$$\overline{u'w'} = -K(\xi) \frac{\partial U}{\partial z} + \overline{u'w'}_{cb} F(\xi) \quad (10)$$

where

$$K(\xi) = m \frac{\overline{w'}^u}{w_{cld}} z_{cld} G(\xi) \quad (11)$$

and

$$\xi = \left(\frac{z - z_{cb}}{z_{cld}} \right)$$

Where the subscript cb indicates cloud base, z_{cld} is the cloud depth and F , K , and G are functions of in-cloud depth.

Can equation 9 be derived by looking at the momentum budget?

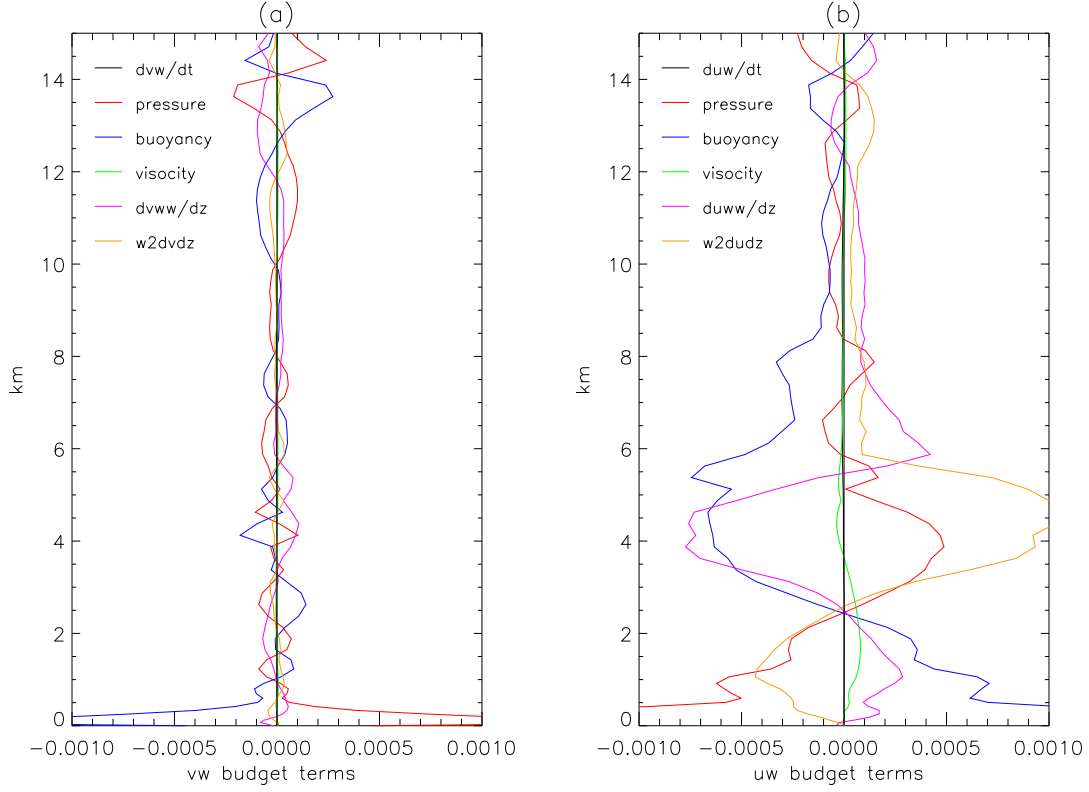
The momentum budget for the CRM is

$$\frac{\partial \overline{u'w'}}{\partial t} = -\overline{w'w'} \frac{\partial u}{\partial z} - \frac{\partial \overline{u'w'^2}}{\partial z} - \frac{\overline{w' \partial p}}{\rho \partial x} - \frac{\overline{u' \partial p}}{\rho \partial z} + \frac{g}{\theta_v} \overline{u' \theta'_v} + F_v \quad (12)$$

where p is pressure, g the acceleration due to gravity, θ_v virtual potential temperature, F_v viscous term.

The rate of change of momentum is equal to advection (gradient term plus turbulent transport), pressure gradient, buoyancy force and viscosity. In equilibrium the rate of change of momentum will be zero. The only CRM runs set up to output the momentum budget terms were r1006 and r6121. Looking at the CRM results, the viscosity term is very small, Figure 4 (plot from r6121) and Figure 5 (plot for r1006) and can be neglected.

Figure 4: Terms in the momentum budget for 6121(a) vw and (b) uw. (Note the v component of wind is zero, hence the small terms.)



In the case of the pressure gradient terms the first part is assumed to be small and can be neglected.

Hence at equilibrium

$$0 = -\overline{w'w'} \frac{\partial u}{\partial z} - \frac{\partial \overline{u'w'^2}}{\partial z} - \frac{\overline{u'}}{\rho} \frac{\partial p}{\partial z} + \frac{g}{\theta_v} \overline{u'\theta'_v} \quad (13)$$

All the other terms are not negligible, Figures 4 and 5.

Examining the various terms apart from the gradient term;

Buoyancy term

Using Grant (2006) arguments, the mass flux approximation can be used

$$\frac{g}{\theta_v} \overline{u'\theta'_v} \sim \frac{m}{w_{up}} \frac{g}{\theta_v} \theta_{v,up} u_{up} \sim \frac{g}{\theta_v} \frac{\theta_{v,up}}{w_{up}} \overline{u'w'} \quad (14)$$

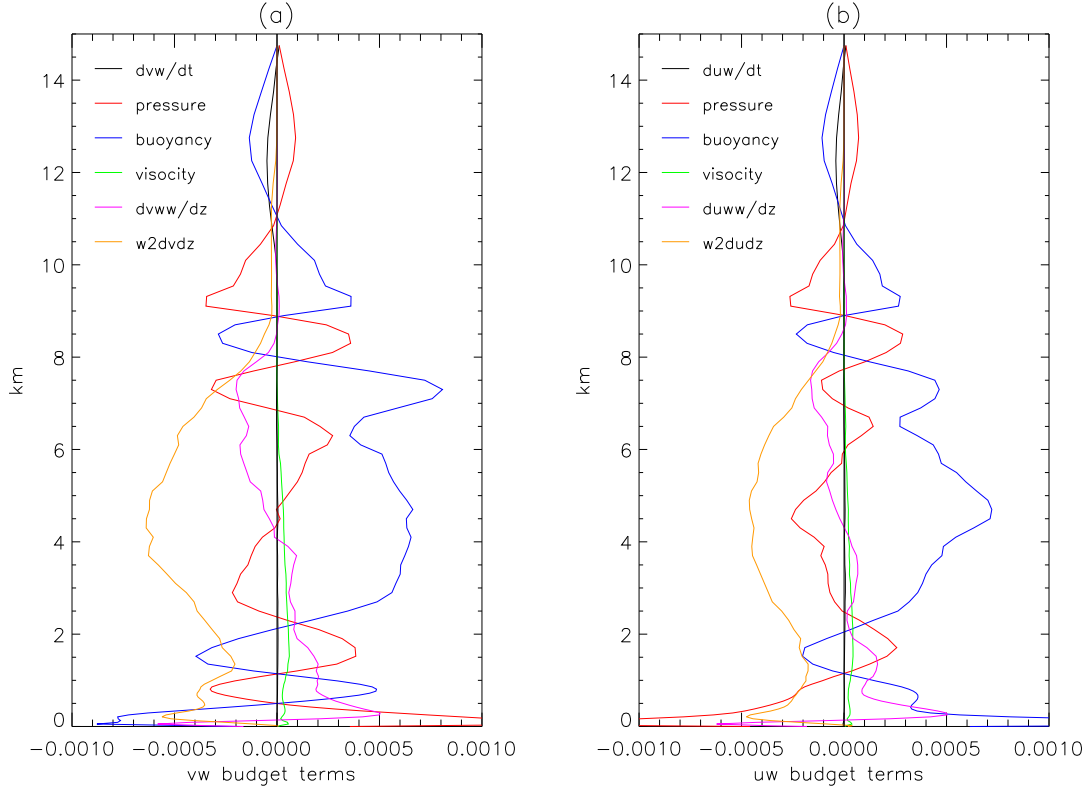
where $m u_{up} \sim \overline{u'w'}$, m is the updraught mass flux, the subscript up indicates quantities in the convective updraught. But this does not explain the shape so Grant tries

$$\frac{g}{\theta_v} \overline{u'\theta'_v} \approx a \frac{g}{\theta_v} \frac{\theta_{v,up}}{w_{up}} \overline{u'w'} + b \overline{w'w'} \frac{\partial u}{\partial z} \quad (15)$$

where a and b are constants.

We have tried fitting this, using a least squares method (Appendix A), for r1006 and r6121 see Figures 6 and 7. The data used for the least squares fitting is the hourly values

Figure 5: Mean terms in the momentum budget for run 1006.



of various v terms at all levels in cloud for r1006 and the 15minute values of the u at all levels in cloud terms for r6121. This is a very small set of data. The results suggest that the 'a' term may depend on something else as well.

Pressure term

Grant (2006) suggests this can be parametrized by

$$\frac{1}{\rho} \overline{u' \frac{\partial p'}{\partial z}} = A \frac{g}{\theta_v} \overline{\theta_v' u'} + \frac{\overline{w' u'}}{\tau} \quad (16)$$

where $A \sim -0.5$ and τ is a return to isotropy timescale, assuming there is no wind shear. If we try to fit the pressure term of the budget like this we get a good fit with a value ~ -0.5 for A and a τ increasing with slightly with height, see Figure 8 for r1006. (Fit obtained using the hourly data from the CRM for each model level in cloud.) See Figure 9 for r6121, $A \sim -0.75$, τ varies greatly with height. But we have a wind shear - so we should have an extra term involving wind shear ?

Turbulent transport term

Using the mass flux approximation the third order moment can be written as

$$\overline{w' w' u'} \approx \alpha w_{up} \overline{w' u'} \quad (17)$$

Figure 10 and 11 show the plots for r6212 and r1006. The mass flux approximation for the term is not particularly good. The alternative parameterization proposed by Grant (2006) is

Figure 6: Run 1006 fit to the buoyancy term.

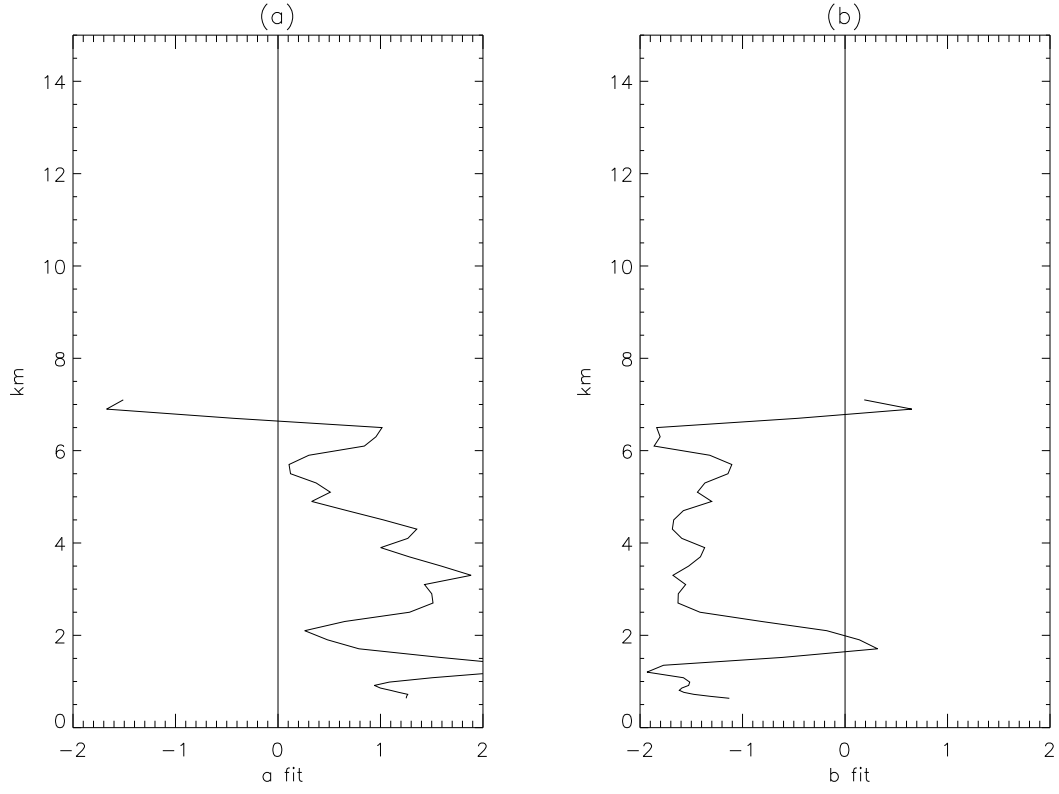


Figure 7: Run 6121 fit to the buoyancy term.

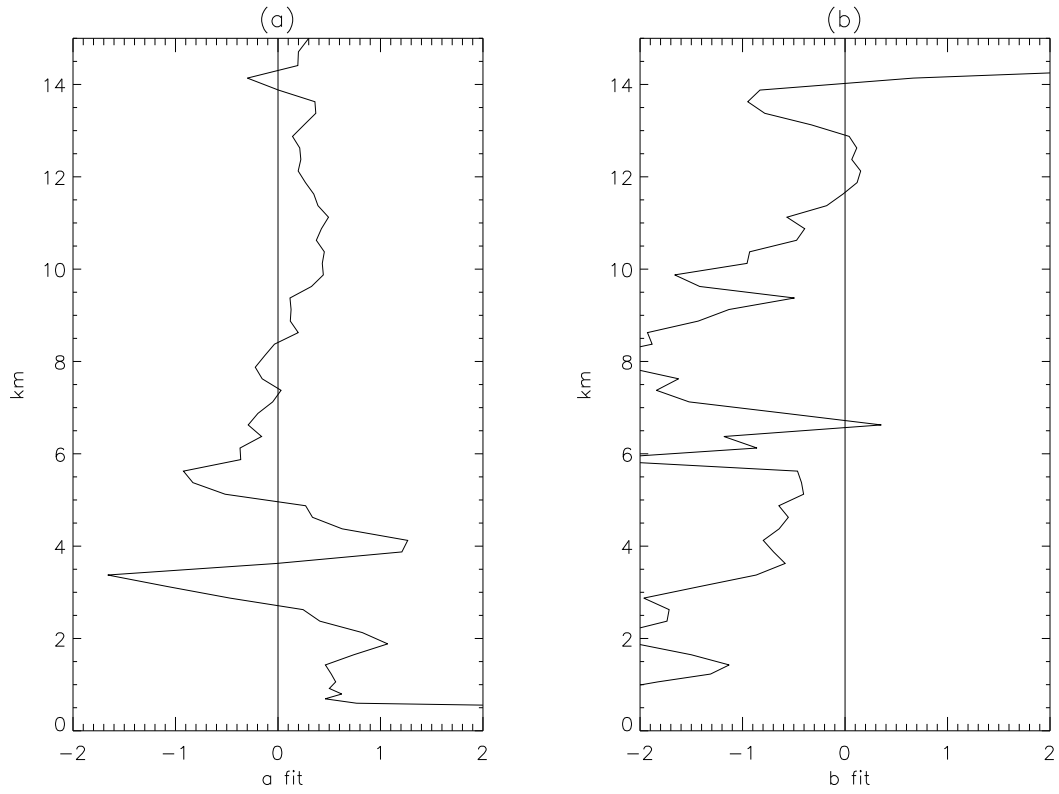


Figure 8: Fit to the pressure term for run 1006.

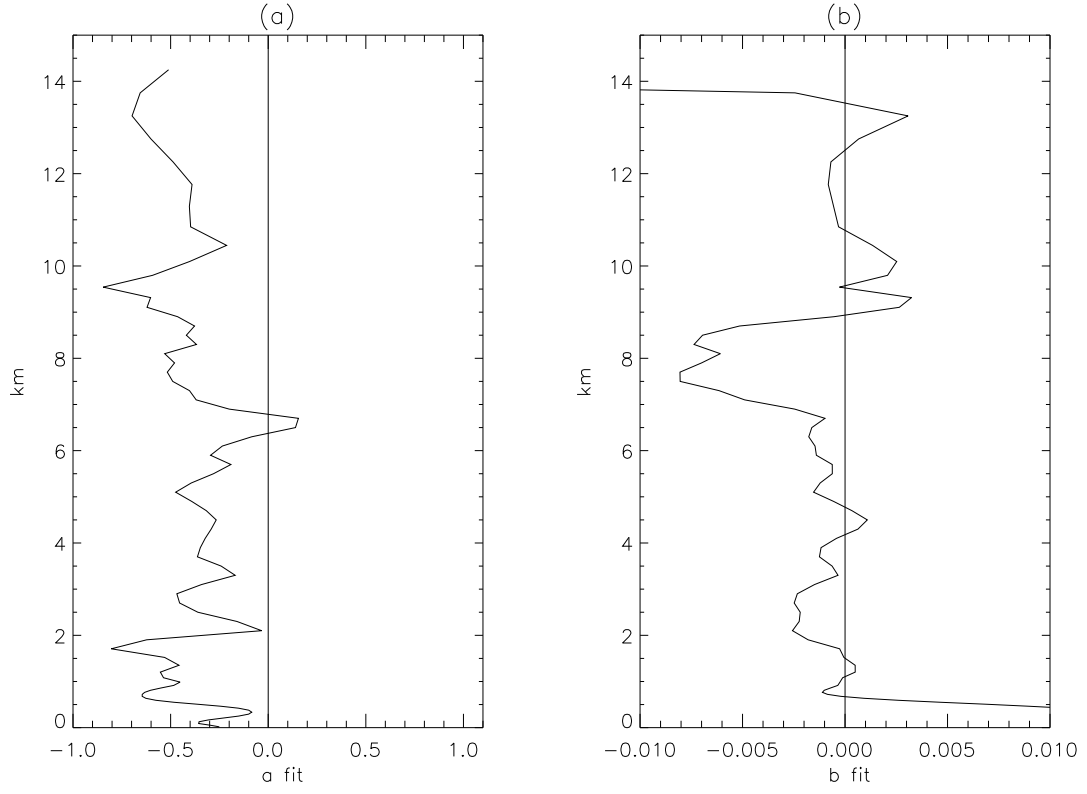


Figure 9: Run 6121 fit to the pressure term.

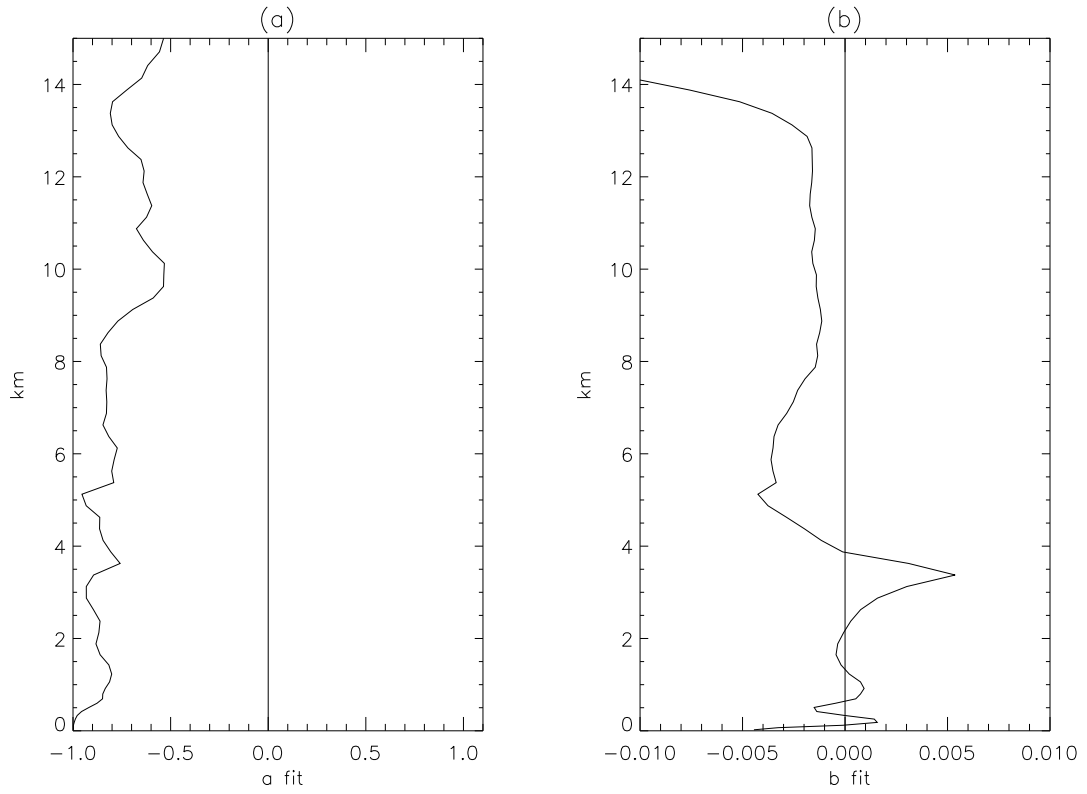
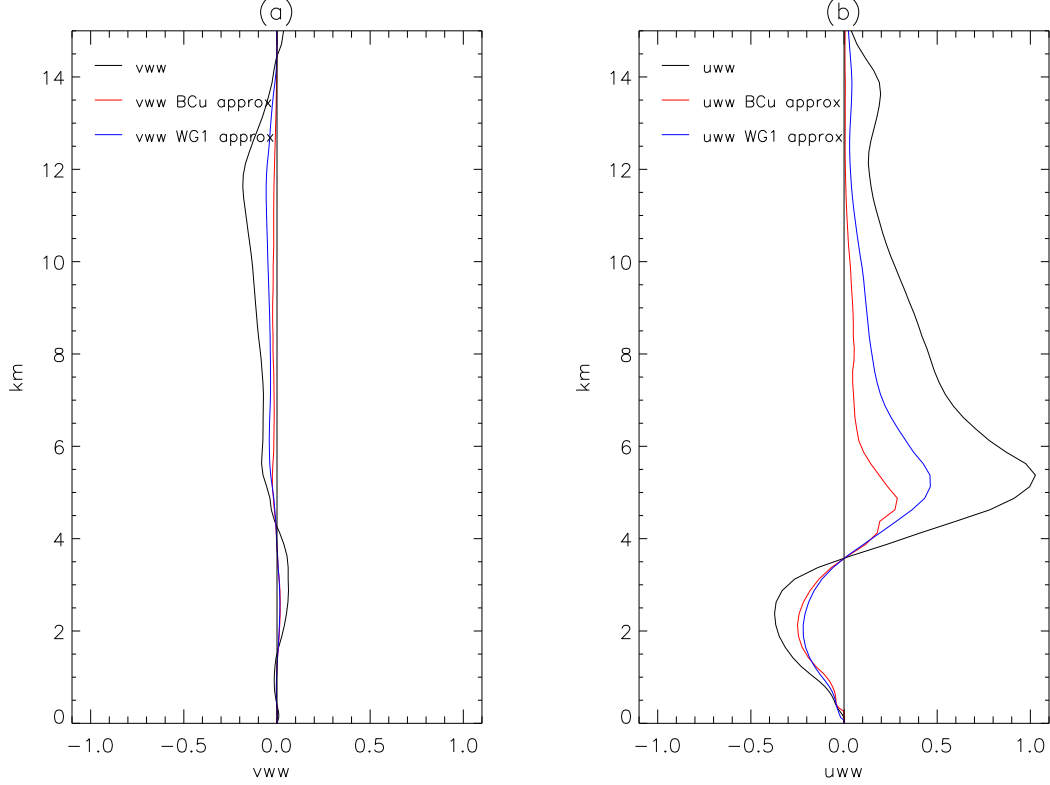


Figure 10: Run 6121 profiles of (a) vww and (b) uww ; plus the mass flux approximation.



$$-\frac{\partial}{\partial z} \overline{w'^2 u'} \approx \beta \overline{w'^2} \frac{\partial u}{\partial z} + \overline{w' u'_{cb}} \frac{w_*}{z_{cld}} F(\xi, \frac{m_b}{w_*}) \quad (18)$$

Putting all the terms together assuming the fits are good gives

$$0 = [(1-A)b - 1 + \beta] \overline{w' w'} \frac{\partial u}{\partial z} + \overline{w' u'_{cb}} \frac{w_*}{z_{cld}} F(\xi, \frac{m_b}{w_*}) + \frac{\overline{w' u'}}{\tau} + (1-A) \left(a \frac{g}{\theta_v} \frac{\theta_{v,up}}{w_{up}} \overline{u' w'} \right) \quad (19)$$

which does resemble equation 9.

2.3.1 Validity of gradient / non-gradient approach

We tested the validity of the gradient/non-gradient approach directly by using the hourly means from the CRM runs and looking at $\overline{u' w'}$ versus $\overline{w'^2} \frac{\partial u}{\partial z}$. We tried fitting the following equation to the hourly model level data

$$\overline{u' w'} = a \overline{w'^2} \frac{\partial u}{\partial z} + b \quad (20)$$

where a and b are constant for each model level. See Figures 12 and 13 for results from r1002 and r2003. Some evidence of dependence on gradient. Problems as wind profiles used have no gradients above 6km initially and the gradients in later hours are very small.

2.3.2 Analysis of the gradient part.

Since $\overline{u' w'}$ depends strongly on $\overline{w'^2} \frac{\partial u}{\partial z}$, we can model $K(\xi)$ as a functions of $\overline{w'^2}$. This can be expressed as $m w^{up}$, where w^{up} is the mean vertical velocity inside the plume. To keep

Figure 11: As figure 10 for run 1006.

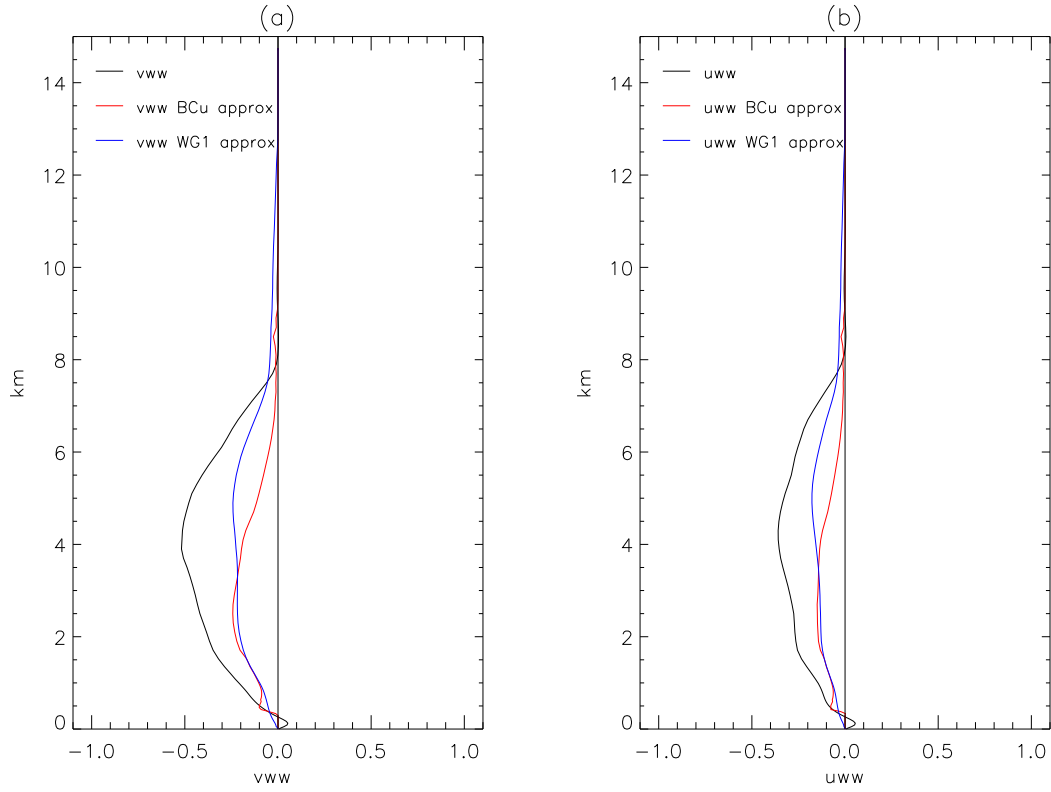


Figure 12: Run 1002, plots of a and b coefficients from trying to fit a gradient and non-gradient part.

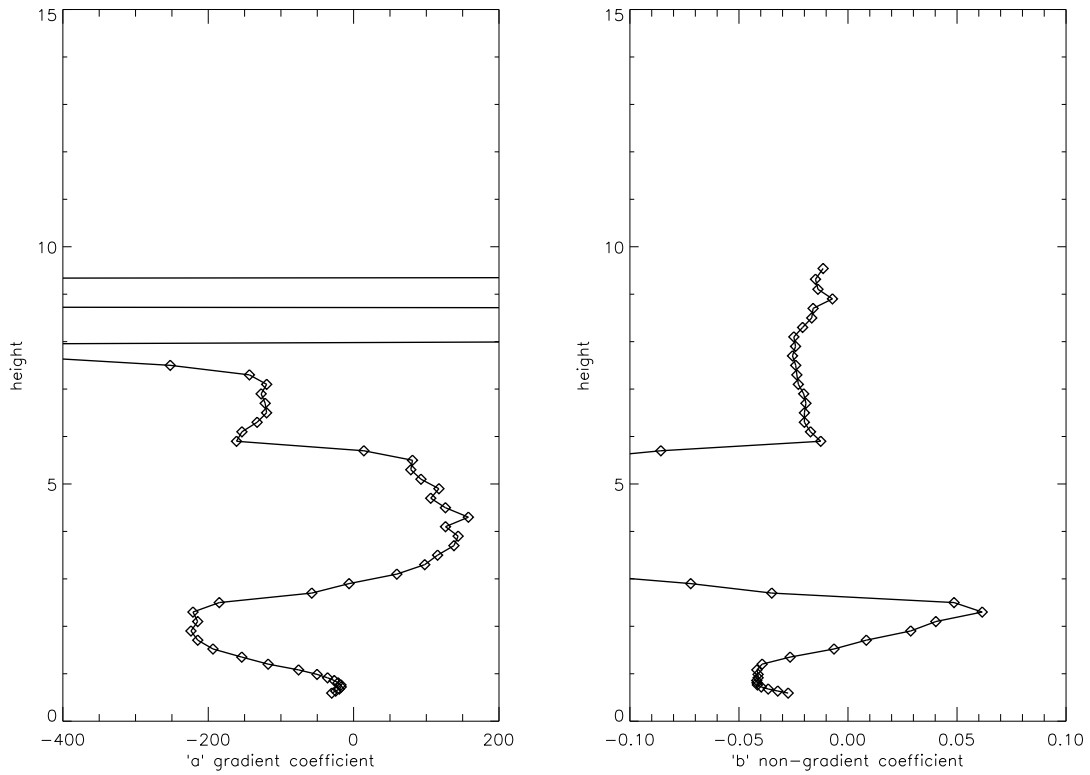
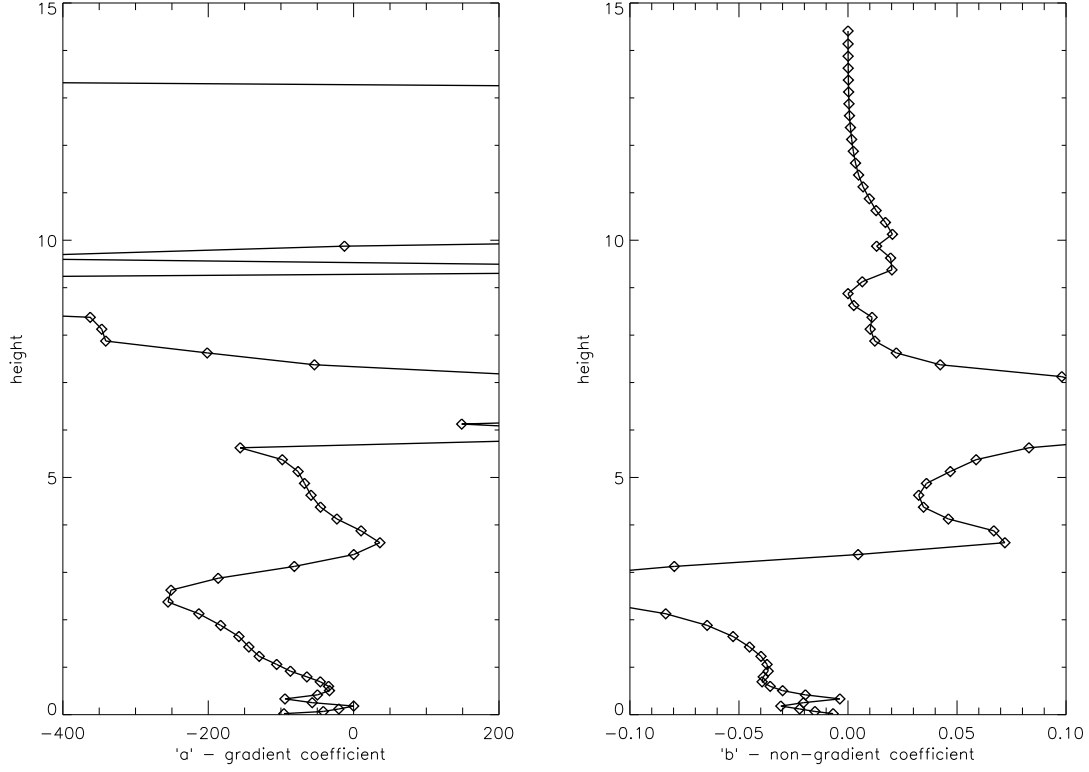


Figure 13: Run 2003 profiles of a and b from trying to fit a gradient and non-gradient part.



the dimensions for the whole expression for the gradient term correct then a length scale and a velocity scale are required. The obvious choice for a length scale is the cloud depth. A velocity scale can be provide by w_{cld} . This gives Grant's (2003) expression for $K(\xi)$ as

$$K(\xi) = m \frac{w_{up}}{w_{cld}} z_{cld} G(\xi) \quad (21)$$

and

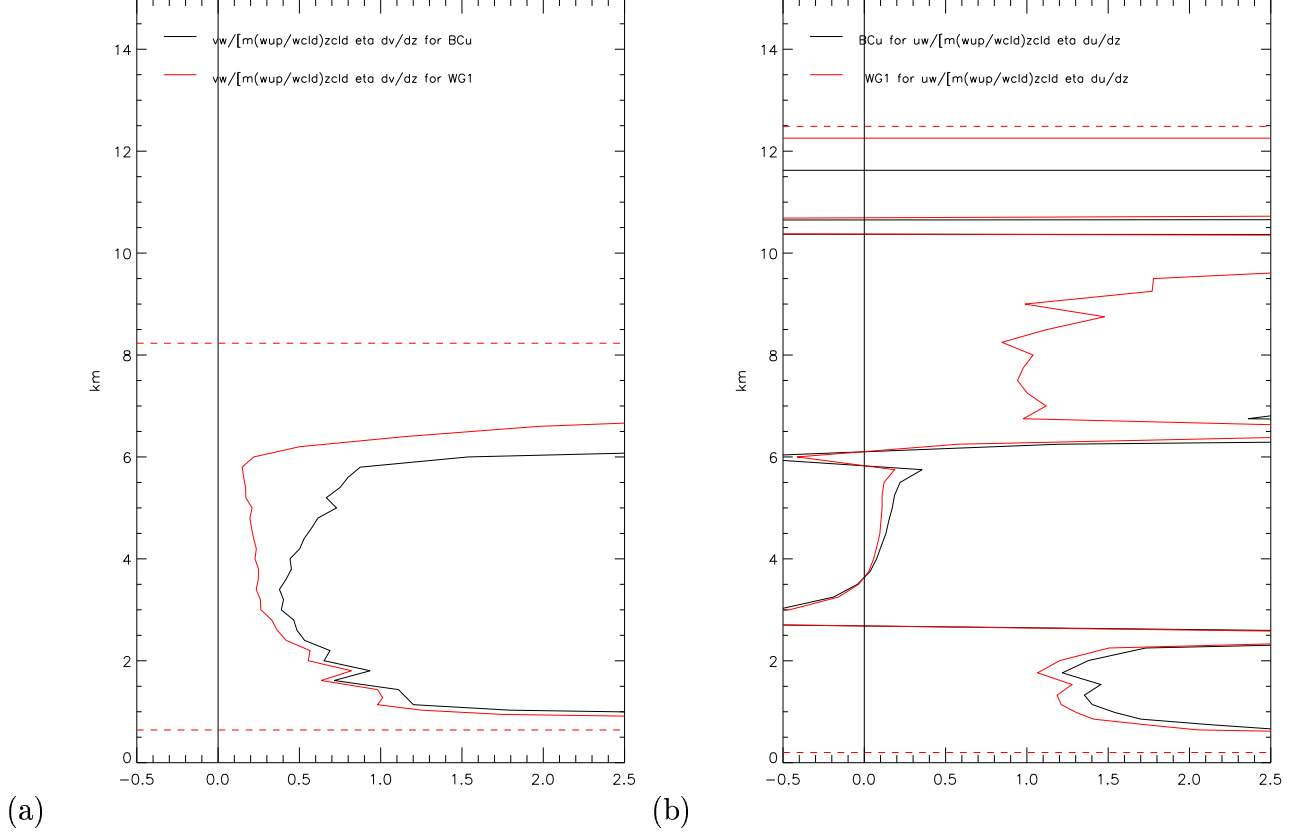
$$\xi = \left(\frac{z - z_{cb}}{z_{cld}} \right)$$

We need to find an expression for $G(\xi)$. Assuming the non-gradient part of the flux is small then $G(\xi)$ can be determined by dividing the total flux by the rest of the gradient term. Plots of $\overline{w'v'}/(w^2 dv/dz)$ (not shown) suggest that $G(\xi)$ may depend on height in cloud. Assuming $G(\xi) = a\xi$ and the other terms in K are replaced by the CRM values of mass flux etc, then looking at Figure 14(a) suggests that a value of around $a=0.3$ may be reasonable for the cold air outbreak. The GATE case does not provide a very clear picture of what to choose but the plot (fig 14(b)) is not inconsistent with $a=0.3$.

The Gregory Rowntree (1990) mass flux scheme has no equation for the vertical velocity in the updraught so for our parametrization scheme an expression for w_{up}/w_{cld} where w_{cld} is the in cloud convective velocity scale is required. Analysis of the CRM simulations show a reasonable approximation for the updraught vertical velocity is given by :

$$\frac{w_{up}}{w_{cld}} = \sqrt{\left(\left(\frac{w_{up,cb}}{w_{cld}} \right)^2 + \left(1 - \left(\frac{w_{up,cb}}{w_{cld}} \right)^2 \right) \left(\frac{z - z_{lcl}}{z_{fr} - z_{lcl}} \right) \right)} \quad (22)$$

Figure 14: Estimates for a in the function for $G(\xi)$ for (a) run 1002 and (b) run 2003.



if the height is less than the freezing level, where z_{fr} is the height of the freezing level, and

$$\frac{w_{up}}{w_{cld}} = \frac{w_{up,peak}}{w_{cld}} \left(\frac{z - z_{fr}}{z_{top} - z_{fr}} \right) \quad (23)$$

above freezing level where z_{top} is the top of the cloud and $w_{up,peak}$ is the peak value of w_{up} . The peak value of w_{up} occurs at the freezing level. Our CRM results show that the peak value of the updraught vertical velocity is fitted well by (see Fig 15b):

$$w_{up,peak} = w_{cld},$$

where the cloud base is below the freezing level. For cases where the cloud base is above the freezing level we have used:

$$w_{up,peak} = w_{up,cb}$$

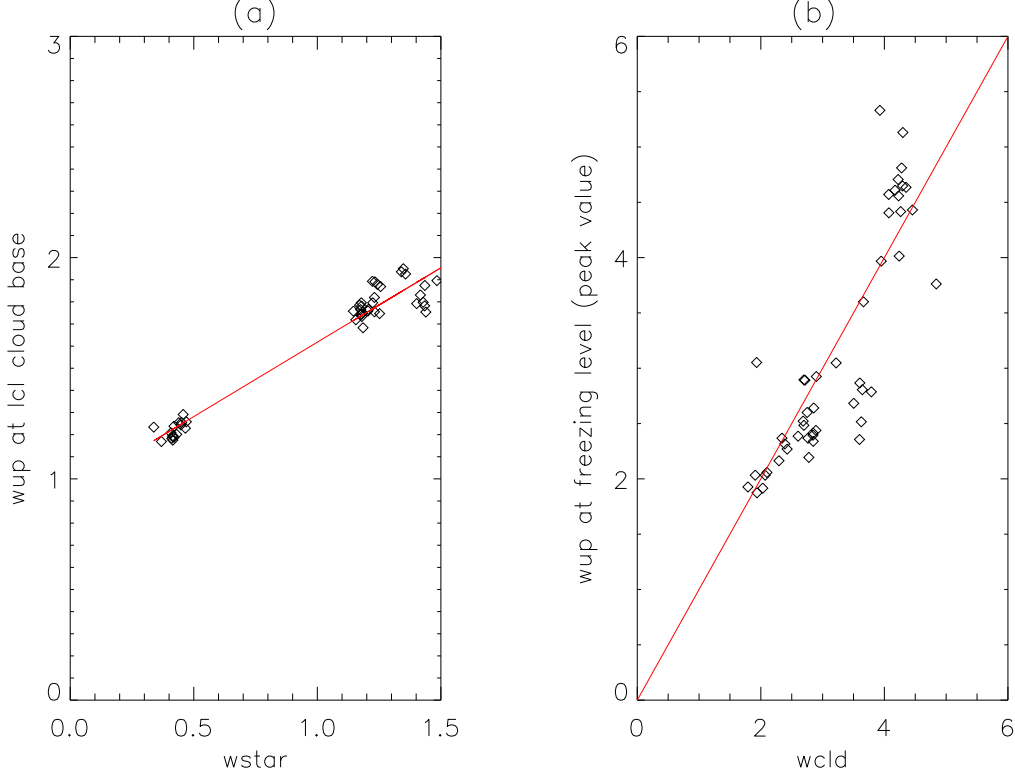
Fitting deep convective CRM results for all the simulations gives the cloud-base vertical velocity as (see Fig 15a)

$$w_{up,cb} = a + bw_* \quad (24)$$

and

$$w_* = \left(\frac{g}{\theta_v} \overline{w'\theta_v'} z_{lcl} \right)^{1/3}$$

Figure 15: Fits to w_{up} at (a) cloud base and (b) the freezing level.



where $a=0.95$, $b=0.67$.

Grant (2003) used the following expression

$$\frac{w_{up}}{w_{cld}} = 2. \left[\frac{p - p_{lcl}}{p_{ntpar} - p_{lcl}} \right] \quad (25)$$

where p is the pressure, p_{lcl} is the pressure at the cloud base (lifting condensation level) and p_{ntpar} is the pressure at the diagnosed top of deep convection.

2.3.3 Analysis of cloud-base fluxes required for non-gradient term.

The non-gradient term requires a cloud-base momentum flux. Trying the same approach as Grant (2003) i.e. that the cloud-base momentum fluxes are related to the surface wind stresses and the change in vorticity across cloud base gives;

$$\overline{u'w'}_{cb} = \delta \overline{u'w'}_0 - \gamma m_b z_{lcl} \left(\frac{u_{ntml+1} - u_{ntml}}{z_{ntml+1} - z_{ntml}} \right) \quad (26)$$

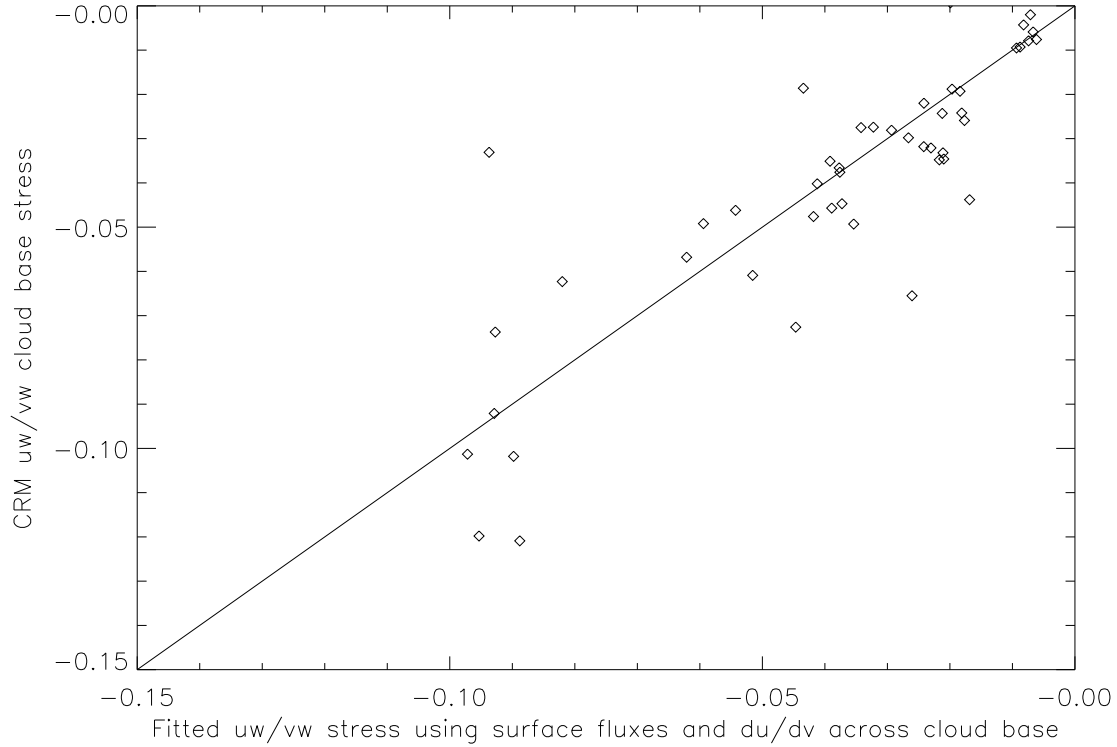
and

$$\overline{v'w'}_{cb} = \delta \overline{v'w'}_0 - \gamma m_b z_{lcl} \left(\frac{v_{ntml+1} - v_{ntml}}{z_{ntml+1} - z_{ntml}} \right)$$

where $ntml$ is the nearest model level to the lifting condensation level.

Values for γ and δ were derived by using a least square method (appendix A) to fit hourly data of surface wind stress, cloud-base wind stress and vorticity across cloud base from all the CRM simulations. The vorticity across cloud base was calculated using the

Figure 16: Fit to CRM cloud-base stress using surface stress and change in the winds across cloud base.



change in wind across neighbouring model levels from the CRM. This approach is not ideal but the vertical resolution of the CRM simulations near cloud base is not high enough to take a different approach i.e. to try to calculate a value across a cloud-base transition region.

Fitting the CRM simulations gives $\delta = 0.7$ and $\gamma = 0.3$, see Figure 16. Grant (2003) had $\delta = 0.185$ and $\gamma = 0.5$ i.e. less dependence on the surface stress but his values came from fitting shallow convection (where the cloud-base transition region may have been resolved) and then slightly altering them for deep convection. (Grant's (2003) shallow values are $\delta = 0.291$ and $\gamma = 0.435$.)

2.3.4 Non-gradient term function of height above cloud base.

Grant (2003) used a function which decreased rapidly with height above cloud base;

$$F = \exp(-(p - p_{tcl})/25000.) \quad (27)$$

We use something fairly similar

$$F = \exp(-\xi) \quad (28)$$

This appears to work based on comparison with SCM (single column 24model results) but there is not much actual basis for using this from CRM results.

Table 1: Difference between the Grant scheme (old turbulence scheme) and the new turbulence scheme.

Property	Grant scheme	new turbulence scheme
mass flux, m	Assumes a shape, scaled by m_b (cloud-base mass flux) from thermodynamic mass flux scheme.	Uses mass flux directly from thermodynamic scheme. (No assumed shape.)
$\frac{w_{up}}{w_{cld}}$	Assumes a shape given by equation 25	Assumes a shape given by equations 22 to 24.
$G(\xi)$	0.3	0.3ξ
$F(\xi)$	profile as equation 27	profile as equation 28
cloud-base fluxes	As equation 26 but different γ and δ	as equation 26

2.3.5 Summary of difference between the new turbulence scheme and the original Grant (2003) scheme.

Both schemes are based on equations 9 to 11 but differ in how the various terms are evaluated. Table 1 gives a summary of the differences in the form of a table.

The most significant differences between the new and original Grant scheme are the assumptions made for the various terms making up the K term. The Grant scheme also tends to work in terms of pressure coordinate rather than height. The version of the Grant scheme referred to later as the **shape tuning** is the same as the Grant scheme but involves an extra factor of

$$1. - 0.75 \left[\frac{p - p_{lcl}}{p_{ntpar} - p_{lcl}} \right]$$

in the calculation of the K term. This extra terms was introduced to improve the NWP winds, and when it was done had no physical justification. This extra factor could now be assumed to be a correction to the $\frac{w_{up}}{w_{cld}}$ profile.

2.3.6 Assessment of new turbulence scheme.

Figures 17 and 18 show the CRM momentum stress profiles together with the profiles making the Grant (2003) assumptions for a turbulence scheme and making the assumptions described here for a new turbulence based scheme. In the case of r1002 the new scheme provides a good representation of the CRM profile and is much better than Grant (2003) scheme. In the case of r2003 the new scheme is too weak at lower levels (<3km) and too strong between 3-5.5km. Above 6.5km the new scheme fails to provide a profile of the correct sign and has a very small magnitude. At almost all levels the new turbulence scheme is better than the original Grant(2003) scheme for the r2003 case.

2.4 Summary of CRM results

The mass flux approach of Kershaw & Gregory(1997) and the turbulence approach of Grant (2003) both have strengths and weaknesses. Results for r1002, Figure 1(a) and (d) how the Gregory-Kershaw scheme assumptions match the stress profile and Figure 17(a) for the new turbulence scheme both show good representations of the stress profile. The

Figure 17: Run 1002, (a) stress profiles , (b) mass flux, (c) wup/wcld.

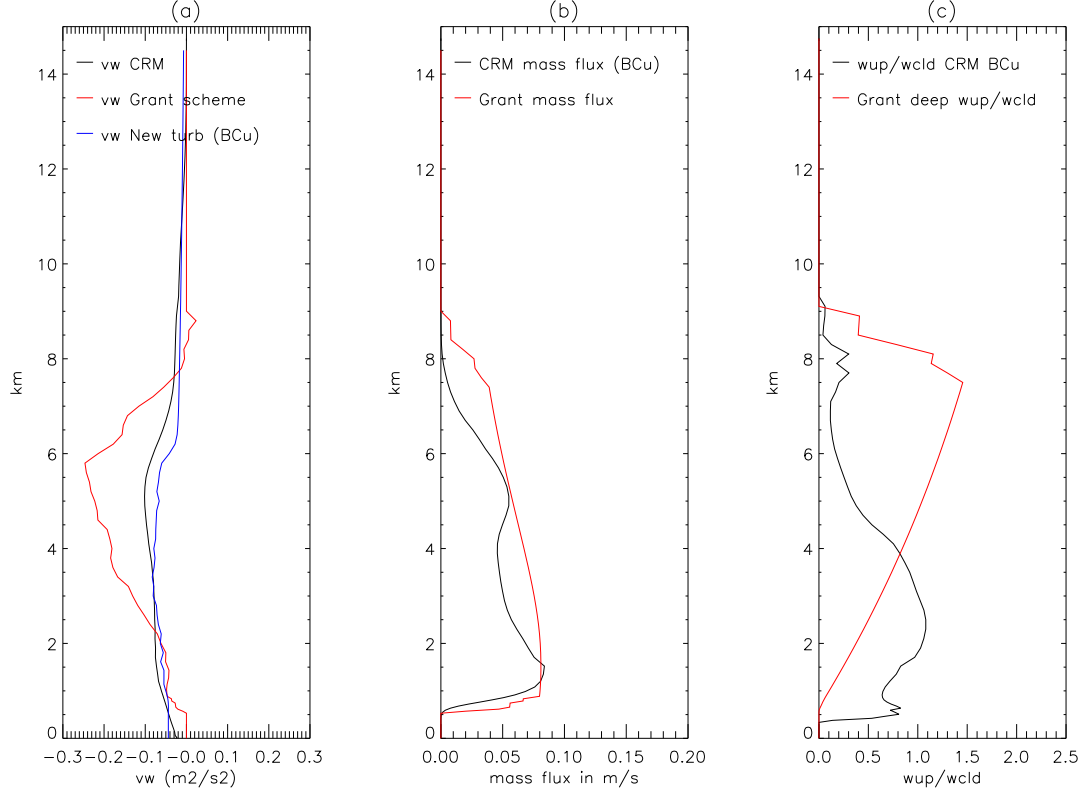
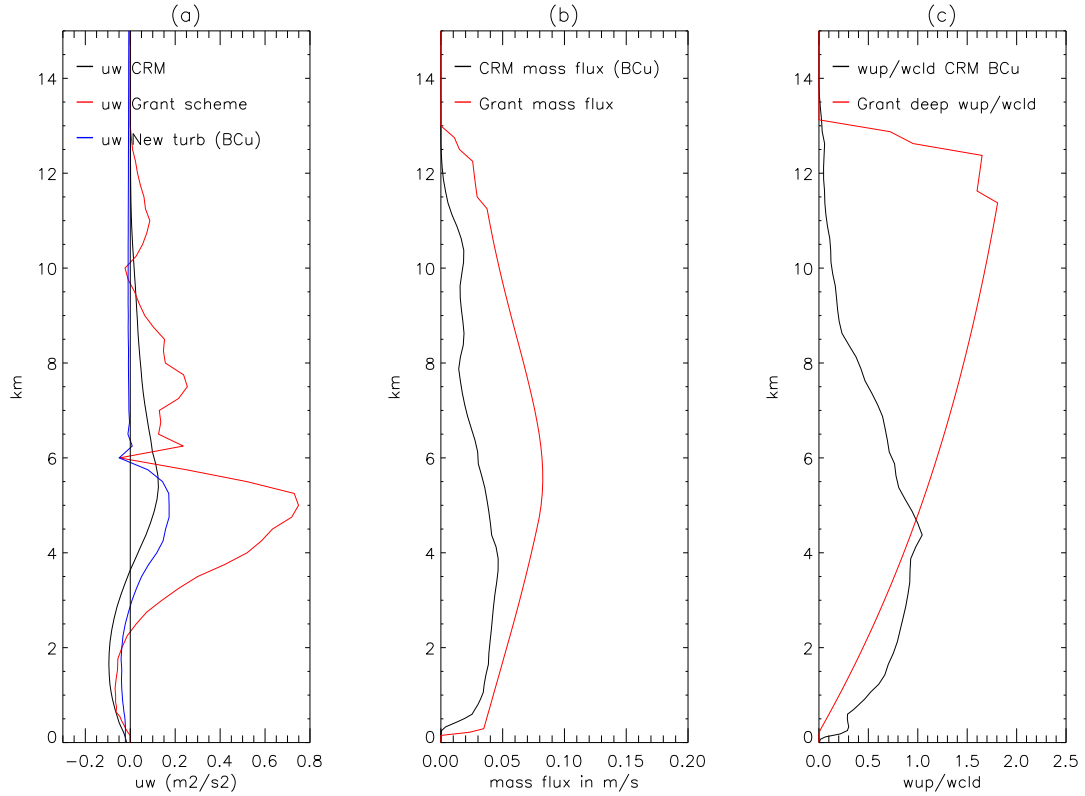


Figure 18: As figure 17but for run 2003.



Gregory-Kershaw scheme being a bit weak towards the cloud top due to the use of the mass flux approximation where as the new turbulence scheme is good throughout the cloud depth. In the case of the Tropical jet, r2003, Figures 2(a) & (d) and 18(a) suggest that the Gregory Kershaw scheme is slightly better, being able to get correct height for cross over from negative to positive stress. Both parametrizations underestimate the stress towards cloud top. This assessment of the two schemes is based purely on diagnostics from the CRM and assumes the mass flux approximation is modelled perfectly. How the schemes will do in a SCM or full UM will depend on partly on how well the thermodynamic mass flux parametrization of the model performs.

3 SCM simulations and comparison with CRM

The first stage in testing any new or revised physics parametrization is to run a single column version of the Unified Model (SCM) to see how well the new scheme behaves for a number of selected test cases. It is possible to set up the SCM to do the same idealised cases as the CRM. The SCM is given the same initial wind, temperature and moisture profiles as the CRM together with the same sensible heat and latent heating at the surface and run for the same period to see how the wind profiles evolve with time. The SCM was set up to run with the 70 vertical levels proposed for use in the operational NWP model. The physics setting of the SCM were similar to an early version of the HadGEM3 climate model before PC2 was included. All convection changes reducing vertical level sensitivity discovered during the 70 level project were included. Basically the convection scheme being used is the Gregory Rowntree (1990) mass flux scheme with;

1. Recent improvement to the downdraught code coming from the 70 level project.
2. Adaptive forced detrainment for deep and mid level convection (but not the smoothed version as this was not available at the time).
3. A four hour RH based CAPE closure. A four hour CAPE closure was used instead of the usual 1 hour to ensure that the SCM deep convection was continuous rather than very intermittent.
4. One sweep of convection per model time step. A 10 minute time step was used.

Four SCM runs were compared for each idealised case;

- (a) Using the Grant scheme (old original deep turbulence CMT scheme).
- (b) Using the Grant scheme (old original deep turbulence CMT scheme) with the shape tuning (a 0.25 reduction in the stress profile near cloud top).
- (c) Using the Gregory-Kershaw CMT scheme for deep convection.
- (d) Using the new deep turbulence CMT scheme.

3.1 Cold air out-break with wind shear

Figure 19 shows the results from the SCM runs for the cold air out-break case using a 10 m/s wind. The SCM profiles plotted are means over the whole period of the SCM run as are the CRM profiles. During the SCM simulation the lifting condensation level rises by 2 model levels. Also deep convection is not present on every SCM model time step. The change in LCL and the intermittent convection may account for the strange wiggles in the SCM profiles around cloud base. The first thing to note is the difference in the mass flux profile between the CRM and all the SCM simulations. This suggests that the thermodynamics of the mass flux scheme in the Unified Model are unable to correctly reproduce the behaviour seen in the CRM simulation. The CRM has a large mass flux near cloud base falling off more rapidly with height than the SCM. This difference in mass flux will have an impact on the parametrization of the deep CMT in the SCM. The stress profile (Figure 19(b)) shows that the old turbulence scheme has too high a value towards cloud top. All the SCM simulations have too low values near cloud base probably linked to the difference in mass flux between the CRM and SCM simulations near cloud base. Looking at the wind increments, the new turbulence scheme performs best near cloud top. The old turbulence scheme with the shape tuning behaves very like the new turbulence scheme for this case. Around 3km all the SCM disagree with the CRM result as the gradients in the stress profiles differ in this region. Below cloud base the new turbulence scheme and the Gregory-Kershaw scheme are too weak, as might be expected given the difference in the mass fluxes. The old turbulence scheme agrees better but this uses an assumed mass flux shape rather than the thermodynamic mass flux.

3.2 Tropical case with low level jet

Results from the tropical jet are shown in Figure 20. The SCM simulations suffer from the same problems as in the cold air outbreak, i.e. the lifting condensation level rises with time and the deep convection is intermittent. In this case the SCM results for the mass flux profile differ significantly towards the top of the cloud, the SCM having a large mass flux. Towards cloud base the CRM mass flux is slightly higher. Looking at the uw stress profiles, none of the parametrized results from the SCM are an exact match to the CRM. All are too weak towards cloud base. All turbulent schemes have a zero stress too low. The Gregory-Kershaw scheme does well in getting the zero stress value at the correct height. As expected the old turbulence scheme is too strong towards cloud top where as the new turbulence scheme is in much better agreement. The old scheme with the shape tuning gives a reduces stress profile higher in the cloud.

The wind increments show good agreement between the new turbulence scheme and the CRM. The Gregory-Kershaw scheme giving wind increments which tend to be too weak apart from the very top of the profile where they are too strong. The old turbulence scheme is too strong particularly above 7km as is the old scheme with the shape tuning. Below cloud base all the SCM are different from the CRM wind increments.

3.3 Summary of SCM results

The SCM results show why the original deep turbulence CMT scheme would tend to have problems; i.e. being too strong at higher levels in the tropics and reducing the winds. The shape tuning introduced to reduce this problem is effective in reducing the bias at higher levels. The new turbulence based CMT scheme reduces the errors at higher levels

Figure 19: Cold air out-break SCM results, (a) V winds increments from convection and boundary layer, (b) vw stress profile, and (c) mass flux profile, (d) wind profile after 10 hours, initial wind profile - dashed line. Key black - CRM, red - old turbulence, blue - Gregory- Kershaw, green - new turbulence, purple- old turbulence with shape tuning.

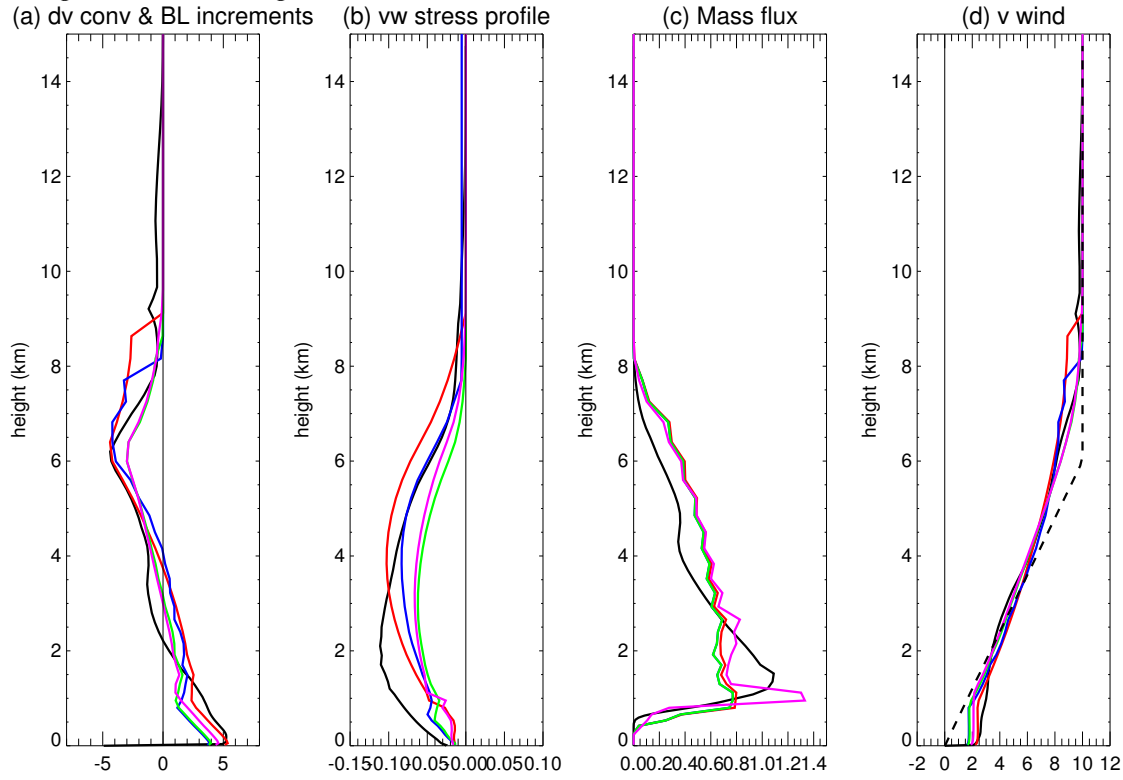
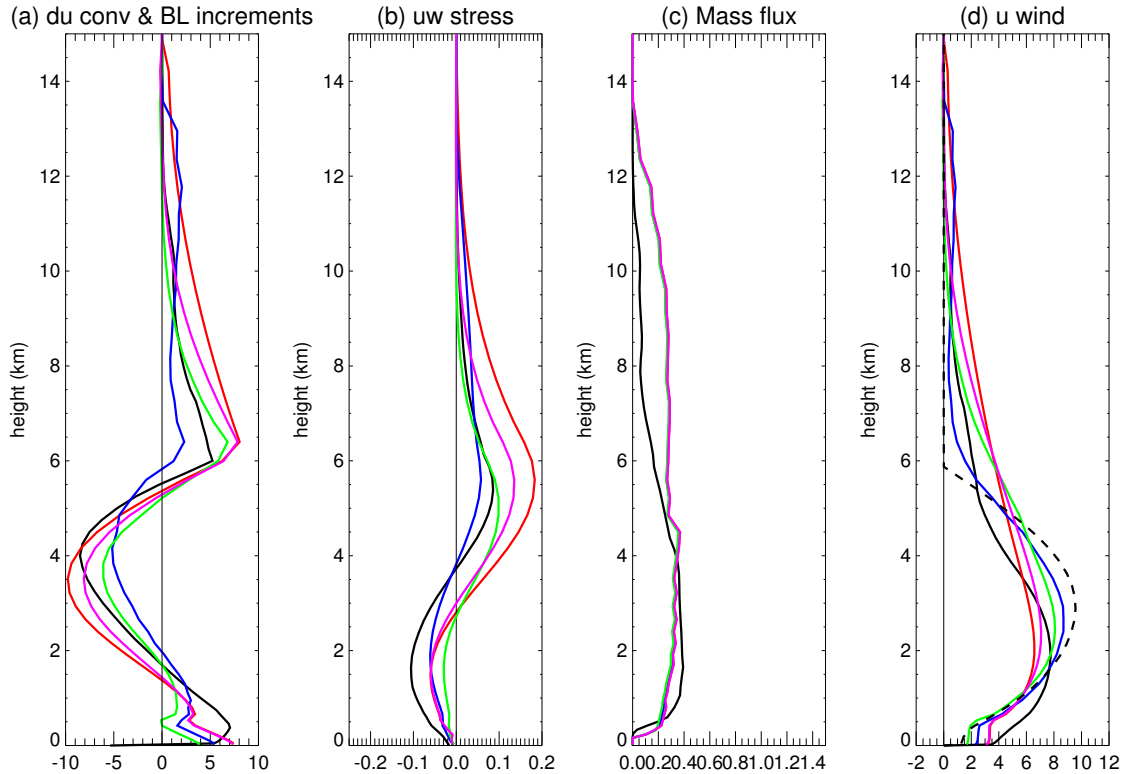


Figure 20: Tropical jet case (a) U increments, (b) uw stress profiles, (c) mass flux, same colours, (d) wind profile after 10 hours, as figure 19.



in cloud further. The Gregory-Kershaw scheme, while tending to give a better fit to the stress profile in the Tropical jet case does not always give a better fit to the wind increments. The Gregory-Kershaw scheme tends to have a slightly different behaviour higher in the convective cloud tending to lead to higher winds increments towards cloud top not always in agreement with the CRM results. On the basis of the SCM results alone it is difficult to deduce whether the new turbulence scheme or the Gregory-Kershaw scheme is the better choice for a deep CMT scheme. All schemes in combination with the boundary layer scheme seem to have problems matching the wind increments below cloud base.

4 Mid-level CMT - an alternative scheme

NWP forecasts suggest that over steep orography a significant proportion of the convection is mid-level. This mid-level convection over orography often operates with a short CAPE timescale (the forecast model uses the w-based CAPE closure and w tends to be high over steep slopes leading to a shorter CAPE timescale). A short CAPE timescale will lead to larger convection increments to temperature, moisture and winds on a time step. Currently the mid-level convection scheme in the UM uses the Gregory-Kershaw CMT scheme which is an explicit scheme. Mid-level convection operating over a few levels using the Gregory-Kershaw scheme can give large noisy CMT increments to wind which in occasionally may be the cause of operational failures.

This section describes an alternative more diffusive like CMT scheme. The diffusive CMT scheme lends itself to being solved in an implicit way making it more likely to

be stable than the Gregory-Kershaw scheme which is solved explicitly. A more stable scheme may be less likely to create such noisy wind increments. From Kershaw et al (2000), equation 3, the parcel horizontal velocity is given by

$$\frac{\partial u^P}{\partial z} = \epsilon (u^E - u^P) + C^u \frac{\partial u^E}{\partial z} \quad (29)$$

where P is for parcel, E environment, ϵ is the entrainment rate and C^u is a non-dimensional coefficient for the pressure term relative to the shear term taken as 0.7 from CRM results. This can be rewritten as

$$\frac{\partial(u^P - u^E)}{\partial z} = \epsilon (u^E - u^P) + (C^u - 1) \frac{\partial u^E}{\partial z} \quad (30)$$

The environment wind profile is known so we can solve for $u^P - u^E$ in integral form via an integrating factor $\exp \int \epsilon dz$, for the case of a constant entrainment rate ϵ . Then

$$d [e^{\epsilon z} (u^P - u^E)] / dz = e^{\epsilon z} (C^u - 1) \frac{\partial u^E}{\partial z} \quad (31)$$

Hence

$$u^P(z) - u^E(z) = (C^u - 1) \int_{z_1}^z e^{\epsilon(z'-z)} \frac{\partial u^E}{\partial z'} dz' + e^{\epsilon(z_1-z)} (u^P(z_1) - u^E(z_1)) \quad (32)$$

It can be seen then that the first term on the right-hand side is close to a diffusion-like specification of CMT, whilst the second term represents the initial parcel momentum excess.

In mid-level convection we expect the initial excess (i.e. the initial parcel wind to be approximately the environmental wind) to vanish so the second term is zero. Then if $\frac{\partial u^E}{\partial z}$ can be treated as constant over the scale $1/\epsilon$ we obtain

$$u^P - u^E = - (1 - C^u) \frac{1}{\epsilon} [1 - e^{\epsilon(z_1-z)}] \frac{\partial u^E}{\partial z} \quad (33)$$

Multiplying by the updraught mass flux, M , gives a diffusive like expression for momentum flux i.e.

$$M(u^P - u^E) = -M(1 - C^u) \frac{1}{\epsilon} [1 - e^{\epsilon(z_1-z)}] \frac{\partial u^E}{\partial z} = -\rho K \frac{\partial u^E}{\partial z} \quad (34)$$

The term $\frac{1}{\epsilon} [1 - e^{\epsilon(z_1-z)}]$ will tend to $z - z_1$ in the limit where $z_1 - z$ is small and to $1/\epsilon$ where it is large.

This alternative scheme has been coded. There are no specific SCM test cases for mid-level convection. The TOGA COARE SCM case generates some mid-level convection allowing the code to be tested to check it works as intended.

5 CMT over orography?

The Unified Model holds winds and temperature on different horizontal and vertical grids. The convection scheme is designed to work on a vertical column. Currently the U and V components of wind are interpolated in the horizontal to the temperature grid for use

in the convection scheme. The CMT increments to U and V are calculated on the T grid and then interpolated back to the wind grids. The bilinear interpolation used is fine over flat sea or land but is not very sensible in regions of steep orography where winds at neighbouring grid points on the same vertical level may be at very different heights. Interpolation of CMT increments back to points with different heights may contribute to some of the operational problems over steep orography. Section 7.4 gives the results from a run where the CMT increments have been zeroed over steep slopes to see how big the impact of applying CMT in the region of orography is.

The Unified Model boundary layer scheme takes a different approach to calculating U and V increments on model levels. The boundary layer scheme calculates dispersion coefficients K on the T grid and then interpolates these coefficients to the U and V grids before calculating the U and V increments using the implicit solver. Lock (personal communication) suggests that this approach could be considered for convective momentum transport if the turbulent approach to CMT is used.

6 Climate simulations

6.1 Description of the simulations

The new deep turbulence CMT scheme and Gregory-Kershaw deep CMT schemes were assessed against the current turbulence based deep CMT scheme with the shape tuning. The control version of the climate model was an early version of HadGEM3 (N96L38 resolution) including the PC2 cloud scheme. The simulations were all 5 years long, and done using UM version 6.6. Five year climate simulations are suitable for assessing the impact of mean changes in the tropics but are not always suitable for getting a clear picture of the mean impact at mid-latitudes due to greater inter-annual variability. The largest impacts of changing the deep CMT scheme are expected to be in the tropics. The climate simulations were assessed by using the climate model validation software which compares a wide variety of model fields against ERA40 analyses, various satellite climatologies and other surface based climatologies.

The new diffusive mid-level CMT scheme was not assessed in a climate simulation. Mid-level convection occurs in the tropics and also in the mid-latitude storm tracks. A longer climate simulation greater than 5 years is probably required to detect the impact of a change to the mid-level CMT scheme at mid-latitudes.

6.2 Results

Climate model validation notes for both simulations were produced showing a complete set of plots for the 5 year mean seasons DJF (December, January, February) and JJA (June, July, August) with comparisons with climatologies where possible.

6.2.1 Gregory-Kershaw deep CMT

Almost all plots show little or no differences between the control and Gregory-Kershaw deep CMT. Figure 21 show the zonal U wind confirming the lack of change. Figure 22 for the 200hPa velocity potential shows one of the few differences, a small improvement which may not be significant.

Figure 21: Zonal mean U component of wind for JJA.

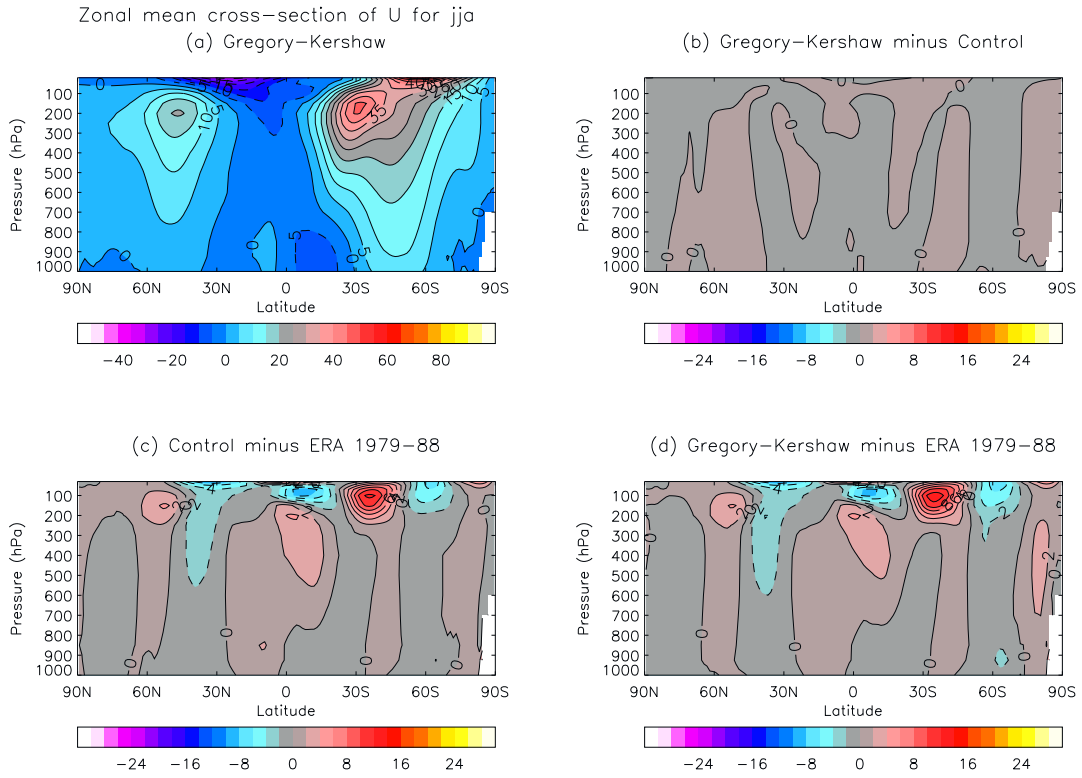


Figure 22: 200hPa velocity potential for JJA.

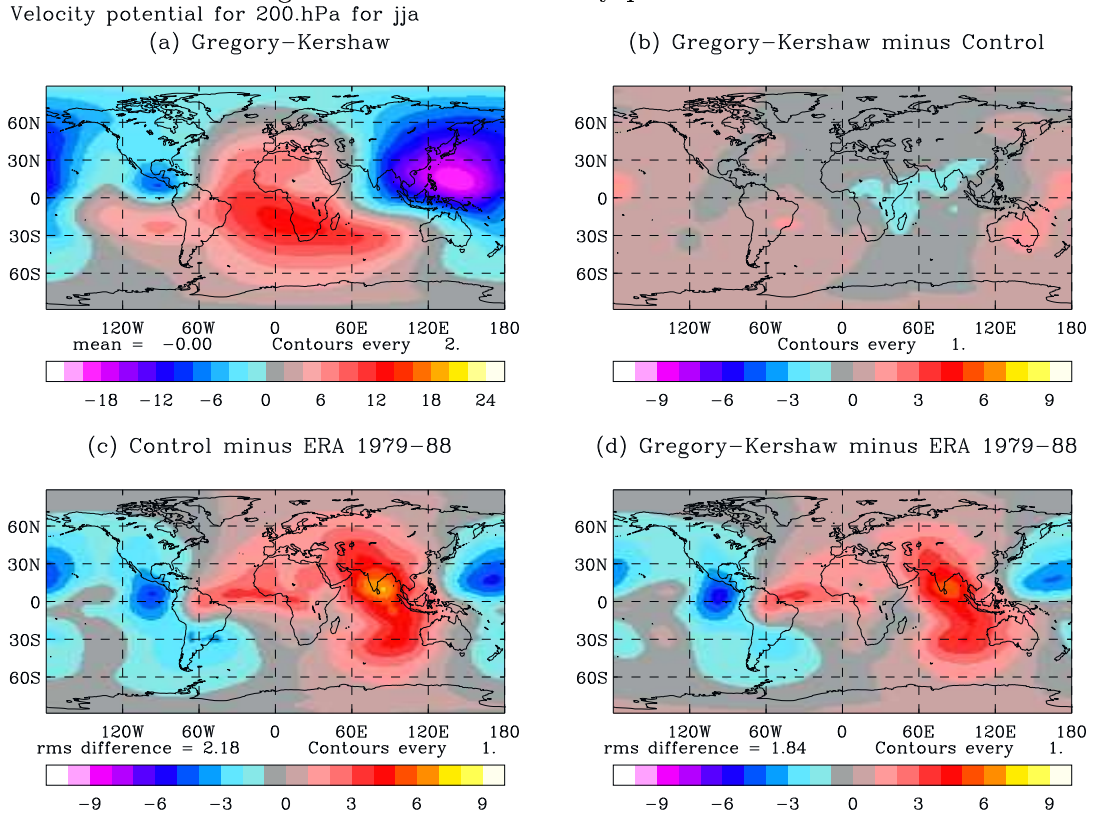
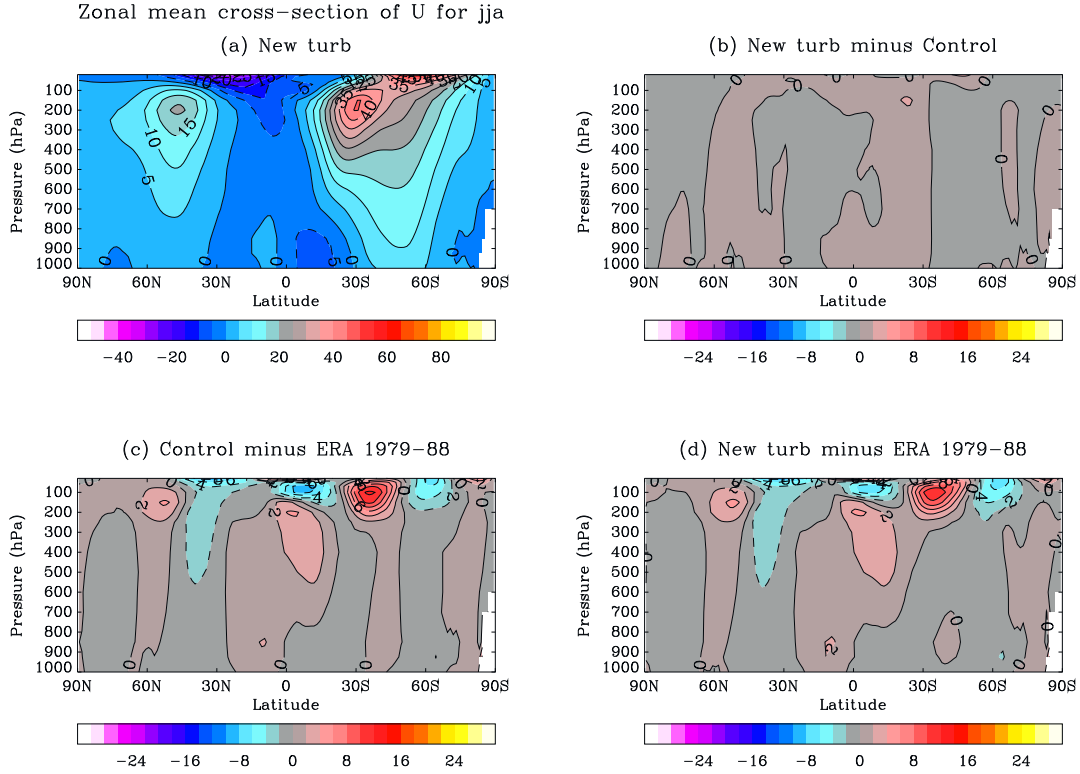


Figure 23: Zonal mean U component of wind for JJA.



6.2.2 New turbulence deep CMT

The standard zonal plots of U and V winds show virtually no difference in the 5 year means, (see Figure 23). Other fields show no significant differences. Only plots of velocity potential at 200hPa show a very small reduction in bias, e.g. Figure 24 for JJA.

6.3 Summary

The climate tests show no significant difference between the different deep CMT schemes. Both new turbulence scheme and the Gregory-Kershaw deep CMT scheme have a better physical basis than the current scheme (old turbulence scheme with shape tuning).

7 NWP suite control tests

7.1 Description of suite control tests

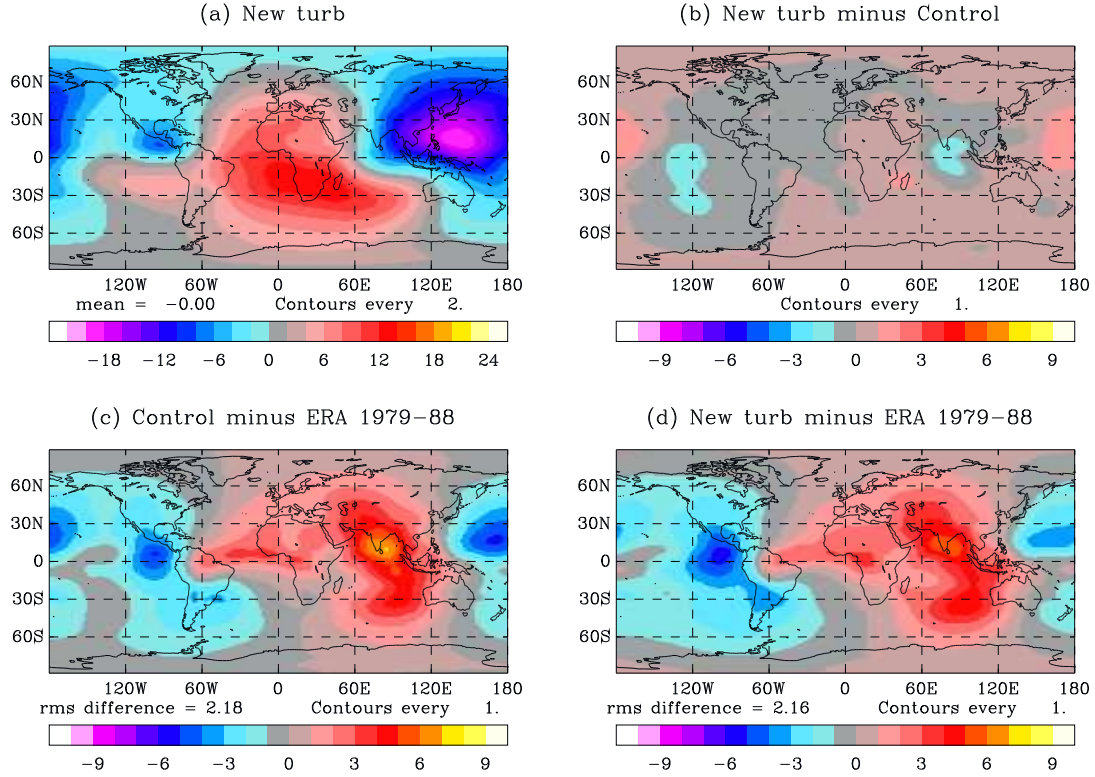
The control job was a N320L70 close to the proposed 70 level physics (as August 2008 when the operational control was PS18) using the deep turbulence based CMT with the shape tuning and the Gregory-Kershaw mid-level CMT scheme. The 70 level control used adaptive smoothed detrainment with a rdet value of 0.75, an early set of CCRAD settings and only 21 boundary layer levels.

A series of 5 winter and 5 summer test cases were run for most test suites. The following suites were run;

sevvb - new deep turbulence CMT, Gregory-Kershaw mid-level CMT

Figure 24: 200hPa velocity potential for JJA compared with the control (b) and ERA (d).

Velocity potential for 200.hPa for jja



- sevvc - Gregory-Kershaw deep CMT, Gregory-Kershaw mid-level CMT
- sevvd - Gregory-Kershaw deep CMT, diffusive mid-level CMT.
- sevve - New deep turbulence CMT x2, Gregory-Kershaw mid-level CMT (Winter cases only).
- sevvf - New deep turbulence CMT but with all CMT increments set to zero over any locations with steep slopes (winter cases only).
- sevnb/sewdb - DJF/JJA N320L70 control (shape tuning Grant scheme i.e. old turbulence), (unfortunately the JJA has only 4 of the same cases the 5th uses a different start date as one of the selected control cases was changed after the CMT test runs were started). JJA verification against obs and analyses are restricted to the 4 common cases.

All cases were started from ECMWF analyses. The verification was done against ECMWF analyses. Analysis has concentrated on using the winter case due to the slight difference in the summer cases.

An additional set of suite control tests were run against a later N320L70 control (known as PS20 with $r_{det}=0.75$ and CCRAD changes). These later additional tests consisted of just 5 winter tests cases run from and validated against Met Office rather than ECMWF analyses. The suites compared are;

- sfaob N320L50 operational PS20 control set up.

sfaoe	N320L70 control (redet=0.75 plus CCRAD changes, shape tuning for deep CMT).
sevvvg	N320L70 new turbulence CMT scheme for deep convection.
sevvh	N320L70 Gregory-Kershaw CMT scheme for deep convection.
sevvk	N320L70 All CMT switched off, i.e. no deep, shallow or mid-level CMT.

The final case, sevvk, was included to see the impacts of turning all CMT off.

7.2 Results of forecasts - Deep CMT

Examining the wind increments for small regions of the tropics shows a strange spike in the wind increments at level 29 for convection, advection and vertical diffusion. Investigation has shown that the spike comes from the vertical diffusion scheme and is probably due to a problem with the formulation of the scheme at the first vertical level at which vertical diffusion starts to operate. Apart from the spike the wind increments from the convection scheme vary smoothly with height.

7.2.1 New deep turbulence scheme

The results from the DJF and JJA case studies do not show a clear signal. In general the changes to most fields are small and in many cases probably not significant. Looking at winds which are directly affected by CMT, there is some evidence that the tropical winds against analyses are improved for periods of T+48 and greater when compared against sondes. Comparison against analyses, Figure 28, for 200hPa show an increase in vector rms errors relative to the shape tuning but a decrease in mean errors. Similar results are true for the southern hemisphere 200hPa winds, Figure 27. Low level tropical winds show an initial decrease in bias but an increase in vector rms errors, Figure 25.

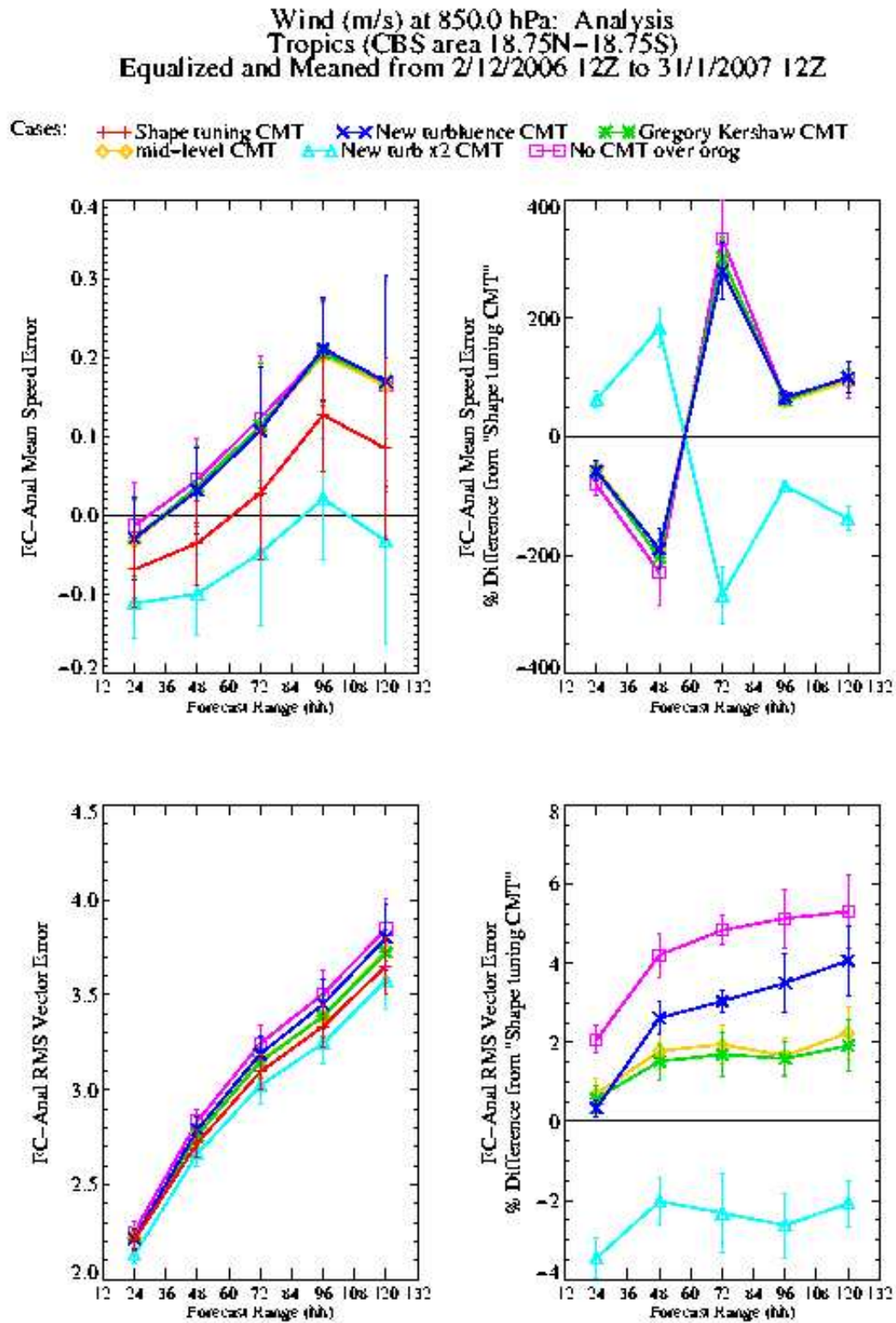
7.2.2 Gregory-Kershaw scheme for deep CMT

The changes to most fields are small and probably not significant. Looking at winds the changes from the control are generally larger for the Gregory-Kershaw scheme than for the new turbulence scheme and in the tropics slightly more beneficial at most forecast periods than the new turbulence scheme, Figure 28 & 25.

7.2.3 Sensitivity test - doubling New deep turbulence CMT increments.

It is surprising that even doubling the new turbulence deep CMT increments does not have a large impact on a winter set of forecasts. There is some evidence in the wind fields that the run with the doubled CMT increments has worse forecast winds at 250hPa at longer forecast periods though there are also results showing small improvements in winds at lower levels (850hPa Figure 25). The implication is that for the time being at least, further ‘fine tuning’ of CMT is likely to have small returns.

Figure 25: 850hPa wind errors against analyses for the Tropics, shows all case studies.



68% error bars calculated using $S/(n-1)^{1/2}$

Figure 26: 200hPa wind errors against analyses for the Northern hemisphere.

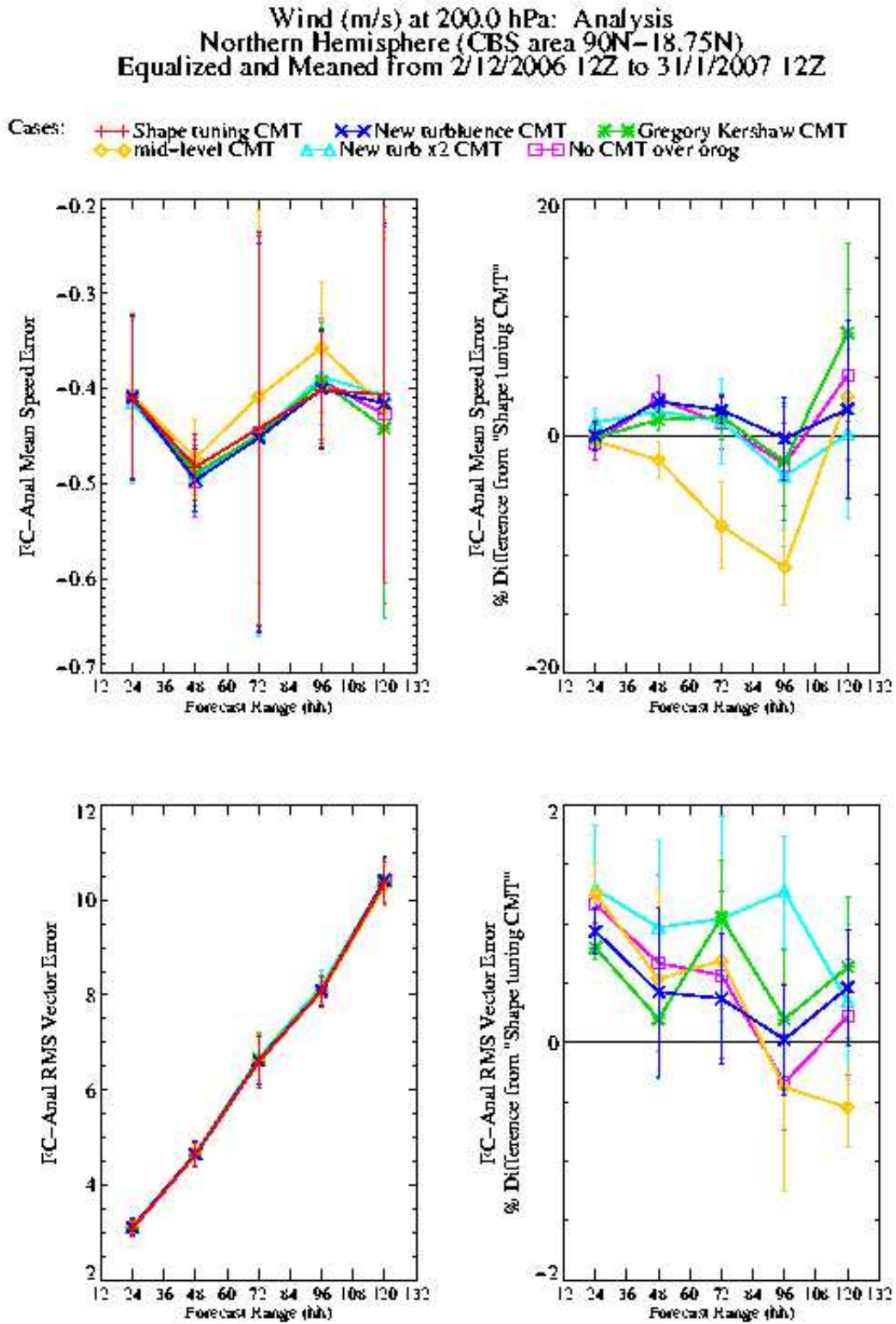


Figure 27: 200hPa wind errors against analyses for the Southern Hemisphere.

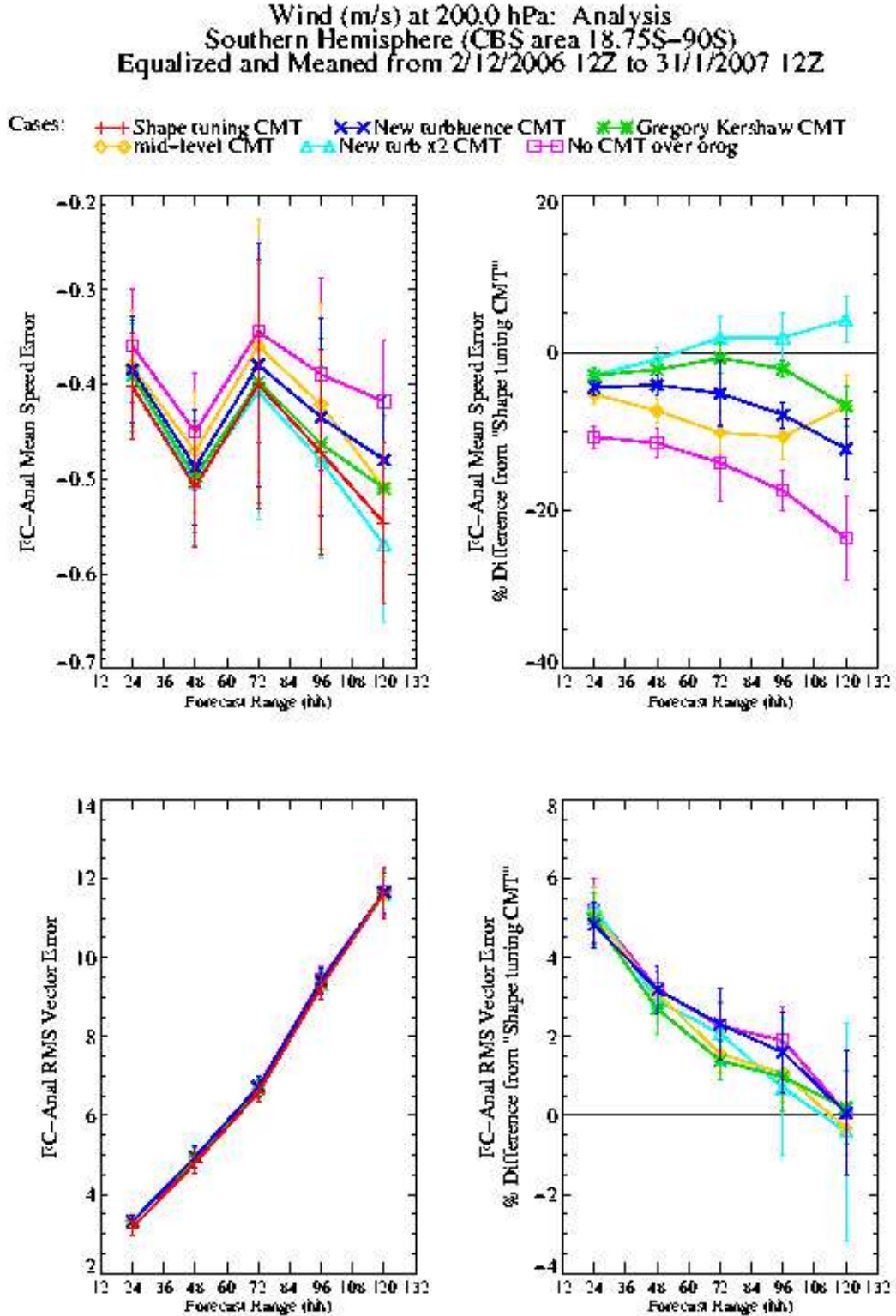
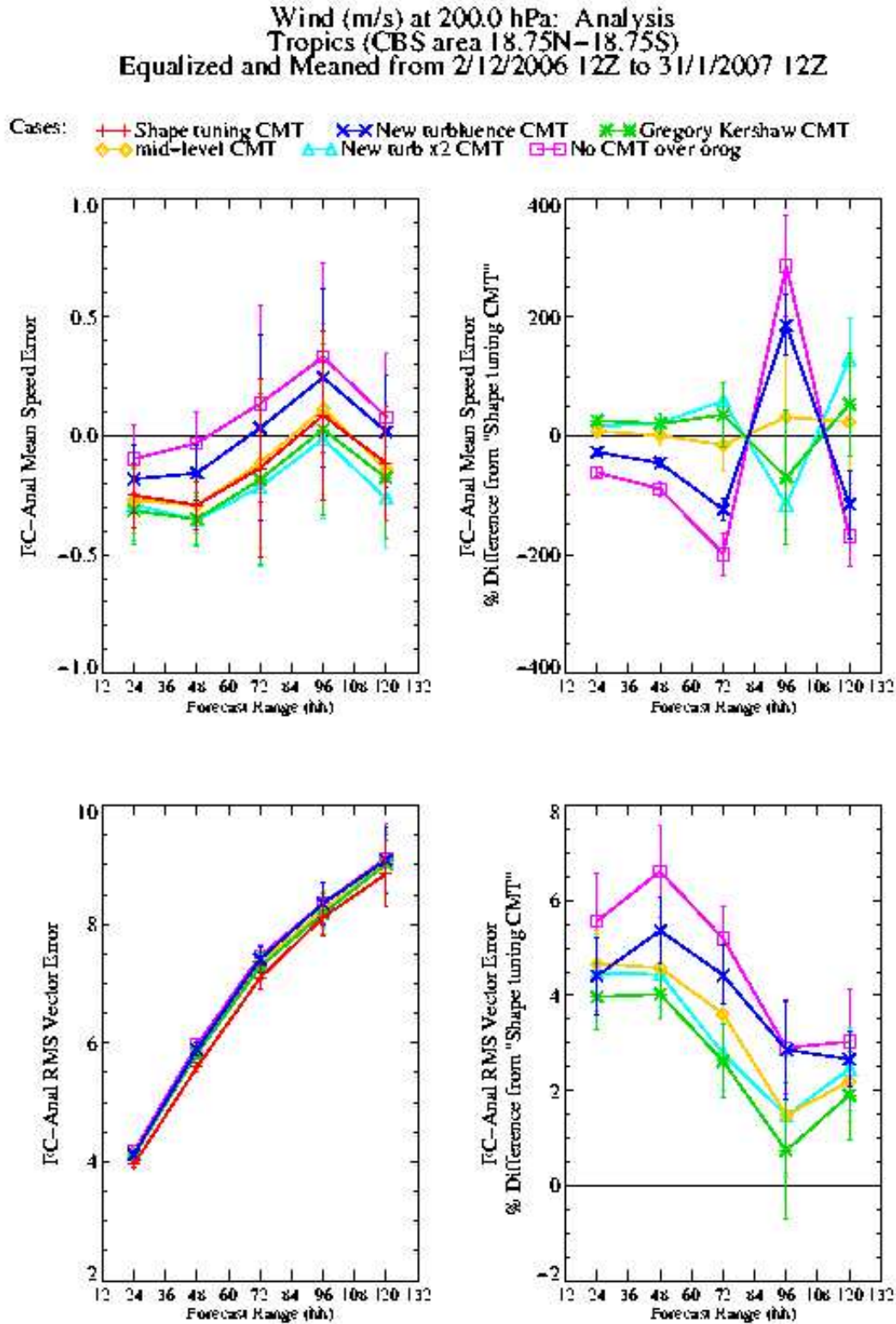


Figure 28: 200hPa wind errors against analyses for the Tropics.



7.3 Results of forecasts - mid-level CMT

Overall the impact of changing the mid-level CMT scheme is very small and possibly not significant. Various standard SCS wind plots for JJA show no significant differences. DJF shows a very slight indication that the original GK mid-level CMT run may be better particularly in the tropics, Figure 28. In the northern hemisphere winter the verification against analyses for vector rms errors slightly favour the diffusive mid-level CMT at longer forecast periods, Figure 26. The southern hemisphere shows little difference.

The intended benefit of diffusive mid_level CMT is technical, with the ability to solve implicitly.

7.4 No CMT over steep slopes

Zeroing wind increments from CMT over steep slopes removes CMT increments over large fractions of tropical land e.g. over the Andes, the Himalayas, parts of Africa and the Indonesian Islands. Results from the NWP test case suggest removing the CMT increments may tend to degrade the winds particularly in the tropics, Figures 28 and 25 when looking at wind vector rms errors. In fact this particular sensitivity test tends to have the largest impact on the wind vector r.m.s. errors, greater than changing the deep CMT scheme, suggesting that some form of convective momentum transport over orography is important in the tropics.

7.5 Turning all CMT off

Figures 29 and 30 show 850hPa and 200 hPa winds errors respectively for the later set of NWP tests. Both plots clearly show that the suite with CMT turned off has larger wind errors at both 850hPa and 200hPa throughout the 5 day forecast period. Having some form of CMT in the model is important, varying the exact form of the deep CMT (see the other lines on the Figures 29 and 30) has a much smaller impact on the wind errors.

Figures 31 and 32 show the T+24 difference in the U and V components of wind between the runs with and without CMT. The T+24 differences closely resemble the increments to U and V wind coming from the CMT scheme and are made up of components coming from shallow, deep and mid-level convection.

7.6 Summary

It was hoped that the NWP forecast tests might show a clearer difference between the various deep CMT schemes than the climate model simulations where initial errors have plenty of time to feed back on the large-scale circulation. NWP Forecasts start from analyses i.e. “truth” and errors grow with forecast period. Unfortunately the NWP forecast cases show little signal. On the positive side the tests do not show any clear deterioration in the forecast when using the new turbulence scheme or the Gregory-Kershaw scheme both of which have a better physical basis than the current scheme.

8 Summary

A turbulence based approach to parametrizing convective momentum transport has been assessed against CRM simulations of deep convection and improved. The new improved

Figure 29: 850hPa winds errors against Met Office analyses for the tropics, later set of NWP tests.

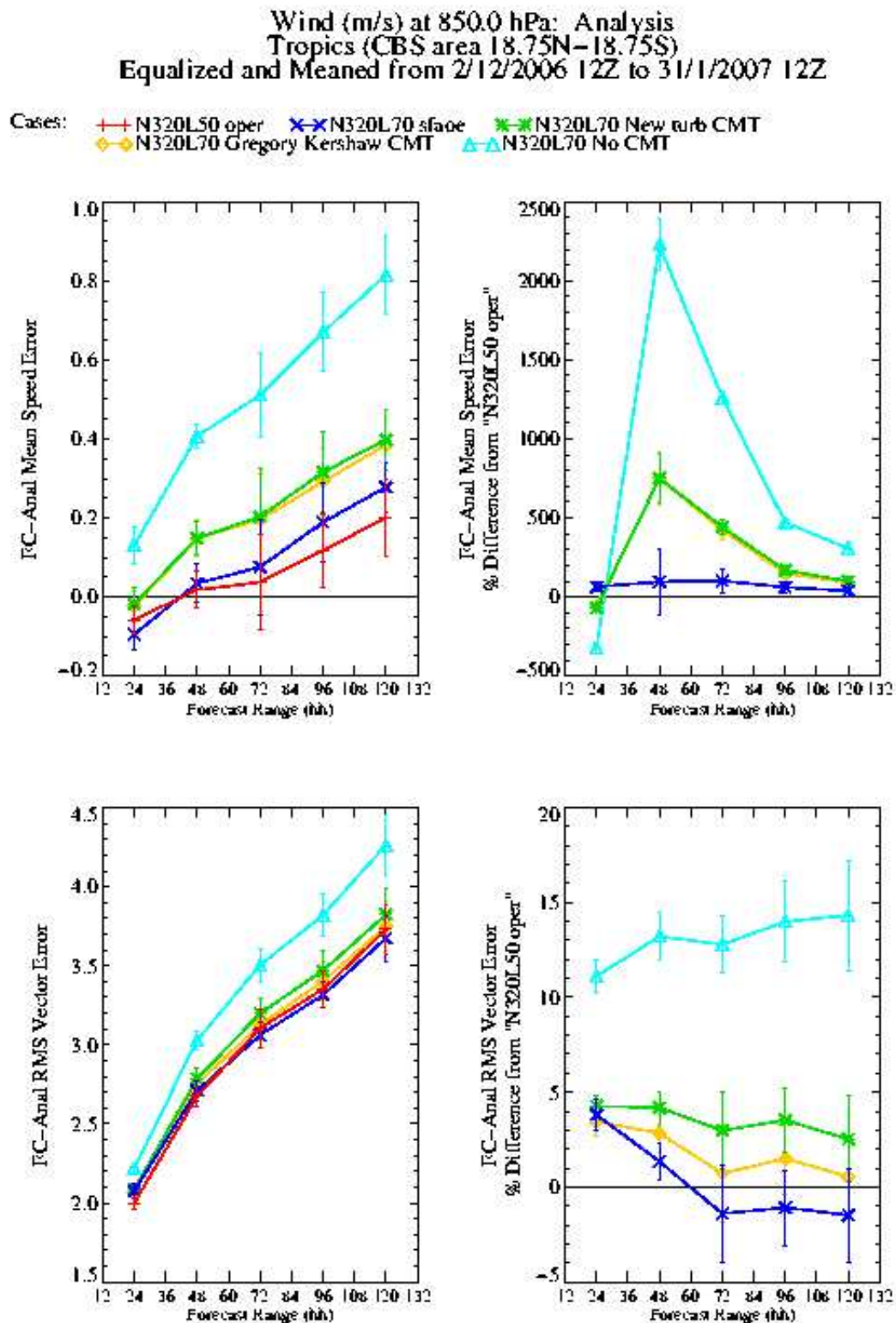


Figure 30: 200hPa wind errors against Met Office analyses for the the Tropics for the later NWP tests.

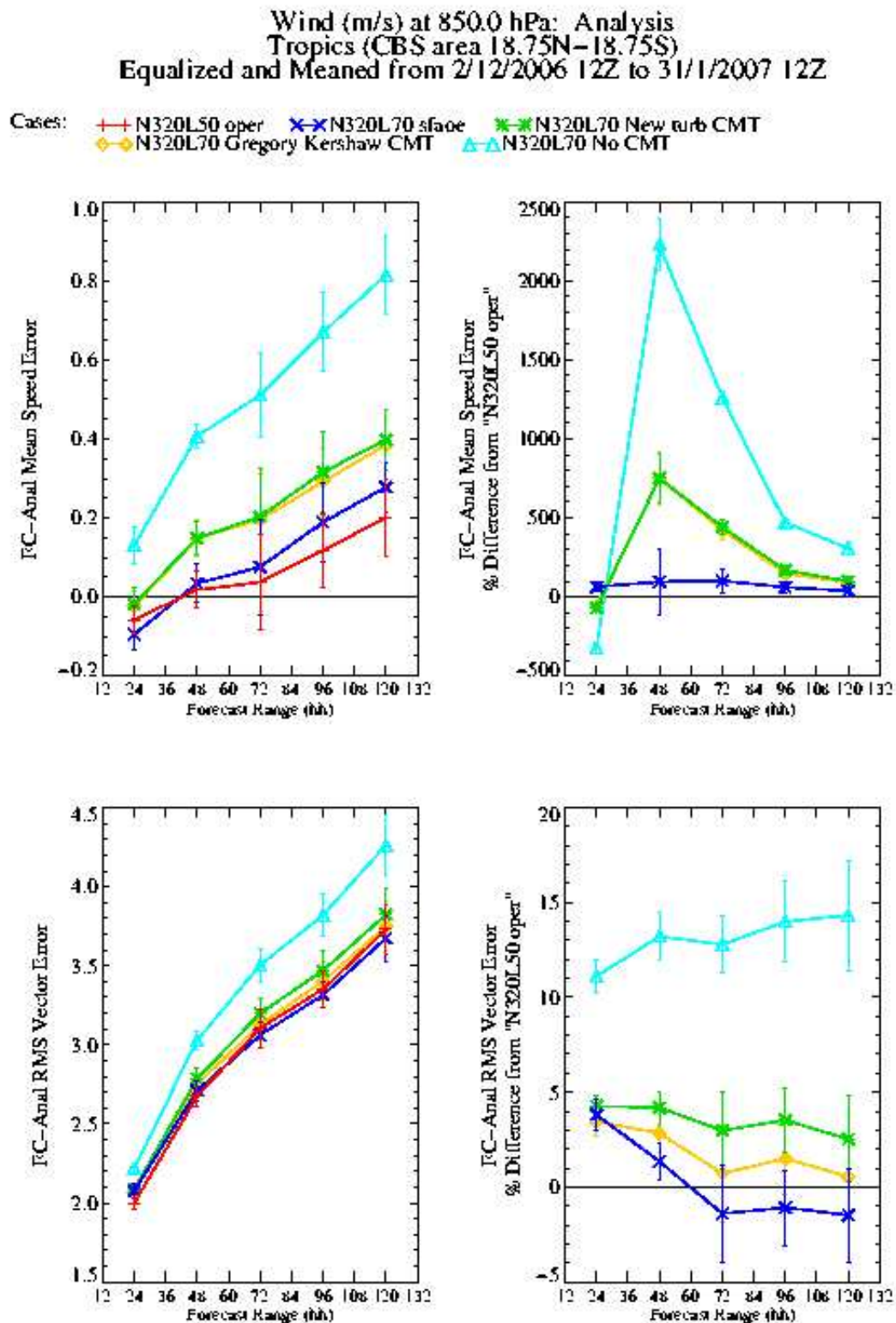


Figure 31: Zonal mean U component of wind for T+24.

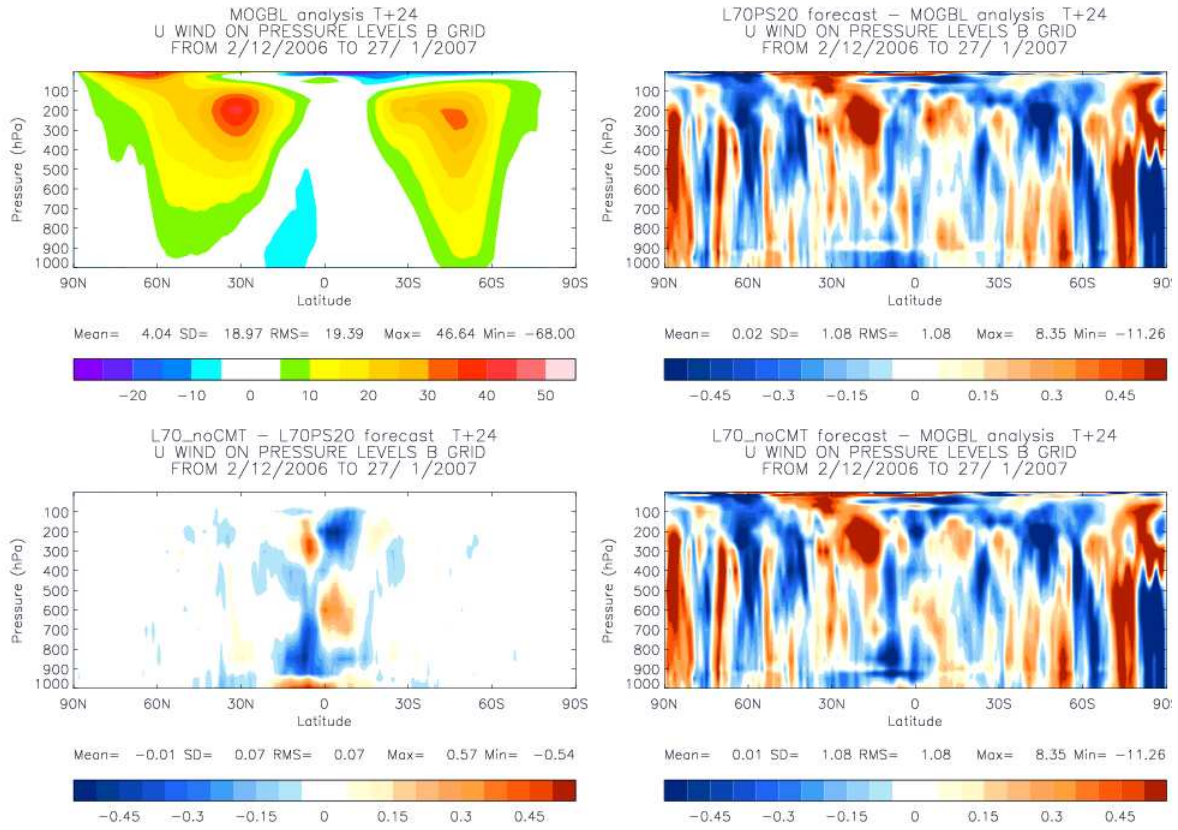
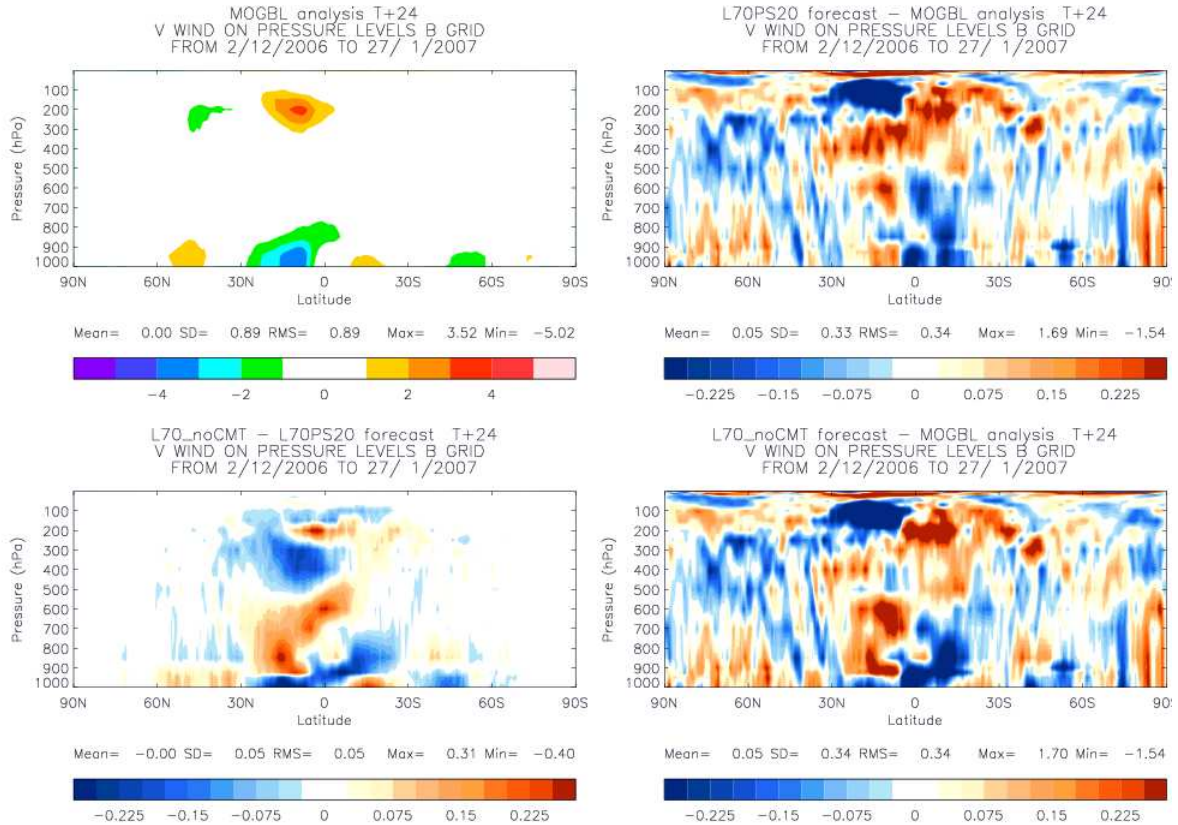


Figure 32: Zonal mean V component of wind at T+24.



turbulence approach has been compared with the old turbulence scheme and the Gregory-Kershaw mass flux scheme. The assessment of the CRM simulations has shown why the shape tuning to the old turbulence scheme gives improvements to the forecasts as it reduces the stress profile where it was too high due to the assumed mass flux profile used with the old turbulence scheme.

The SCM tests, climate simulations and NWP forecast tests are unable to show whether the new turbulence scheme or the Gregory-Kershaw scheme is best. The current mass flux convection scheme still has various problems with its simulation of the thermodynamics of convection which will lead to errors in the UM temperatures in the regions of convection, these temperature errors will themselves contribute to wind errors. It is probable that further refinements to the CMT parametrization scheme will not show improvements until some of the remaining problems with the thermodynamics of the convection are solved.

This study has not investigated the importance of mesoscale convective clusters and their possible influence on CMT (i.e. counter-gradient transport). At present the UM convection scheme does not set out to model these systems. The Carr and Bretherton (2001) reanalysis suggests that such systems do not have a large impact, though recent work by Bechtold (personal communication) suggests they may be important in modelling strong westerly wind bursts in the tropics.

8.1 Recommendations for further work

8.1.1 Work to improve convective thermodynamics

Recent NWP 70 level suite control tests have shown that altering the thermodynamic properties of the convection scheme (i.e. smoothed versus non-smoothed adaptive detrainment) can have a large impact on the tropical winds. The impact on the tropical winds due to this type of change tends to far exceed those due to changes in the CMT scheme.

8.1.2 Convection over orography

This study has shown, section 7.4, that the impact of CMT over orography is large and cannot be neglected. Due to the model grid (i.e. winds at different locations to temperature and moisture) the method used currently to calculate CMT over steep slopes is not ideal. It may be worth trying to recode the turbulence CMT scheme to calculate the local K for the gradient term and non-local terms on the temperature grid but pass these terms to the boundary layer solver to be added to the boundary K terms. The boundary layer scheme then interpolates the K terms to the u and v grids. The combined terms could then be used in the boundary layer solver to calculate implicitly the winds on the u and v grids.

8.1.3 Modelling Mesoscale systems

It may be timely to revisit the work discussed in section 1.3, some of which suggests significant impacts of mesoscale organization.

8.1.4 Problems seen at cloud base and below

The results from section 3 comparing the SCM against the CRM suggest there is a problem modelling the cloud-base stress and the momentum flux below cloud base. This may be due to problems with the convective closure used in the convection parametrization scheme tending to give a lower mean cloud-base mass flux.

Appendices

A) Least squares fit

For a set of data where x , y and z are known at points i and we want to find a and b

$$z_i = ax_i + by_i \quad (35)$$

then minimising S

$$S = \Sigma [z_i - (ax_i + by_i)]^2 \quad (36)$$

so that $\frac{\partial S}{\partial a} = 0$ and $\frac{\partial S}{\partial b} = 0$ gives;

$$\Sigma [ax_i^2 + by_i x_i - z_i x_i] = 0 \quad (37)$$

and

$$\Sigma [ax_i y_i + by_i^2 - z_i y_i] = 0 \quad (38)$$

which can be solved to find the best values of a and b .

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