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COMBINING NON-LOCAL SCALINGS WITH A TKE CLOSURE FOR MIXING IN BOUNDARY LAYER CLOUDS

Adrian Lock*[1] and Jocelyn Mailhot
MSC, Dorval, Canada ([1] Visiting Scientist from Met Office, UK)

1. INTRODUCTION

Many NWP models use 1.5 order (or TKE) turbulence closures to parametrize transports in boundary layer clouds. These tend to work well only for boundary layers where the thermodynamic probability distributions can be considered Gaussian (eg. stratocumulus) and have traditionally (eg. Lenderink *et al.* 2004) had problems representing the observed boundary layer structure when the distribution is skewed (as in shallow cumulus). A new approach is presented that takes as its starting point the Gaussian part of the Bechtold and Siebesma (1998), hereafter BS, cloudiness scheme and the length scale parametrization of Lenderink and Holtslag (2004), hereafter LH. Scaled non-local functions are then added to represent explicitly that part of the distribution arising from the cumulus elements. Results from single column model (SCM) simulations are presented.

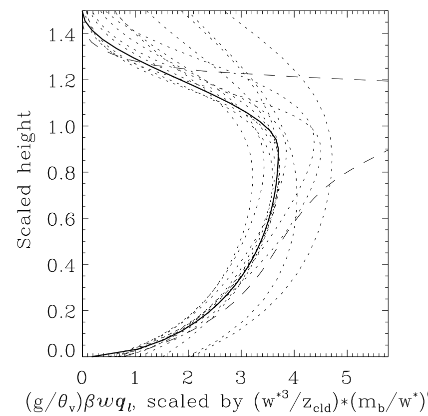

Figure 1: The liquid water flux contribution to the buoyancy flux from LES of shallow cumulus (dotted lines) and Sc/Cu (dashed lines), scaled by S_{wb}. The solid line is the shape function used in the SCM, $f_{wb}(z')$, where $z' = (z - z_b)/z_c$, z_c is the cloud depth, z_b the height of cloud base.

2. A NON-LOCAL PARAMETRIZATION

2.1 The buoyancy flux

Following the approach used by BS, the buoyancy flux is approximated as:

$$\begin{aligned} \overline{w'\theta_v'} &= (1 + r_m q_t)\overline{w'\theta_\ell'} + \alpha\overline{w'q_t'} + \beta\overline{w'q_l'} \\ \beta\overline{w'q_l'} &= g_N\beta(a\overline{w'q_t'} - b\overline{w'\theta_\ell'}) + \overline{w'\theta_v'}^{Cu} \end{aligned} \quad (1)$$

where the g_N term represents the Gaussian part of the distribution (g_N is essentially the cloud fraction, N, parametrized as in BS as a function of the normalised saturation deficit, Q_1). Rather than enhance this term when grid boxes are subsaturated in the mean (as was done by BS), the non-Gaussian or cumulus contribution appears explicitly in (1) as a scaled shape profile:

$$\frac{g}{\theta_v}\overline{w'\theta_v'}^{Cu} = (1 - g_N) f_{wb}(z') S_{wb} \quad (2)$$

where $S_{wb} = (m_b/w^*)^{1/2} w^{*3}/z_{cld}$ is the shallow cumulus buoyancy flux scaling proposed by Grant and Lock (2004), GL (m_b is the cloud-base massflux, parametrized as $0.04w_*$, and velocity scales $w_*^3 = z_b\overline{w'b}_S$ and $w^{*3} = m_b\mathrm{CAPE}$). For the LES of shallow cumulus in GL, g_N is small so that $\overline{w'\theta_v'}^{Cu} \approx \beta\overline{w'q_l'}$. The variation in this term is an order of magnitude between these LES and yet it is mostly explained by S_{wb} (see Fig.1). Figure 1 includes a LES of Sc/Cu (cumulus spreading into stratocumulus, dashed lines). The scaling given by (2) works as well as for the cumulus LES up to about $z' = 0.7$. Above this height, increasingly more of the buoyancy flux is generated by cloud-top radiative cooling in the stratiform cloud layer (at $z' \sim 1$) and so will appear in the Gaussian term in (1) which has not been included in this analysis.

2.2 Cumulus cloud area and liquid water

From physical arguments, GL associated m_b/w^* with the cloud area, and this scaling (not shown) works well for their LES above the cloud-base transition zone ($z \approx 1.1z_b$, from GL). This parametrization, $N^{Cu} = f_N m_b/w^*$ with $f_N(z')$ a shape function, is implemented as a lower limit on the cloud fraction diagnosed by the BS scheme (as an empirical function of $Q_1 = \overline{s}/\sigma_s$, where σ_s is the (parametrized) standard deviation of the saturation deficit, s). To calculate the liquid water content, q_l, the BS parametrization of N is first inverted to give σ_s^{Cu} as a function of N^{Cu}. Then, the greater of σ_s^{Cu} and the standard σ_s is used in the BS parametrization for q_l.

*Corresponding author address: Adrian Lock, Met Office, Exeter, Devon, EX1 3PB, U.K.; email: adrian.lock@metoffice.com

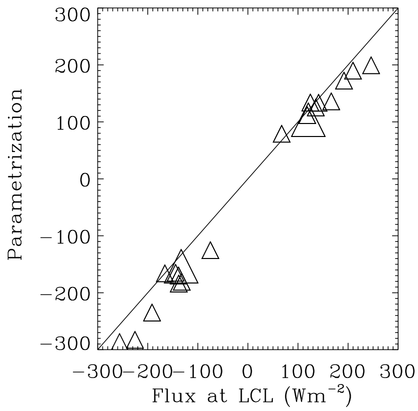

Figure 2: Comparison of parametrized versus LES cloud base fluxes of θ_l and q_t. The former (which are negative) have been multiplied by 10 to allow easier evaluation on the same scale.

2.3 Conserved variable flux parametrization

For non-precipitating shallow cumulus simulations with no radiative fluxes, the flux budgets of θ_l and q_t take the same form. Thus, it is reasonable to assume the flux paramatrization should take the same form too. Grant (personal communication) proposed a flux parametrization of the form

$$\overline{w'\chi'} = -K\frac{\partial \chi}{\partial z} + \overline{w'\chi'}|_{z_{\rm b}} f_{ng}(z') \qquad (3)$$

and demonstrated that unique functions of K and the shape function, f_{ng}, did indeed exist for the wide range of LES in GL ($f_{ng} = 1$ at $z_{\rm b}$ and zero at the surface and cloud-top). The cumulus cloud-base fluxes are here parametrized using the massflux approximation:

$$\overline{w'\chi'}|_{z_{\rm b}} = m_b\left(\chi|_{ml} - \chi|_{(z/z_{\rm b}=1.1)}\right) \qquad (4)$$

Thus the cloudbase fluxes are proportional to the jumps across the cloud base transition zone (and so will tend to be small in well-mixed stratocumulus capped boundary layers, consistent with the philosophy that the non-local terms are representing the effects of the cumulus elements). Fig. 2 shows good agreement is found against LES from GL and also the Sc/Cu simulation (indicated by the larger symbols), although it tends to overestimate $\overline{w'\theta'_\ell}$ slightly. Equations (3) and (4) are also used to parametrize the stresses.

To parametrize K in (3) a TKE closure is used with the mixing and dissipation length scales, l_h and l_ϵ, calculated using the formulation proposed by LH, but adapted for cumulus clouds. In the cumulus cloud layer, the LH length scales are dominated by the stable part of the formulation, $l_s = c_s e^{1/2}/N_{BV}$ where N_{BV} is the Brunt-Vaisala frequency. Here, the following addition is proposed, in order to represent the non-local mixing

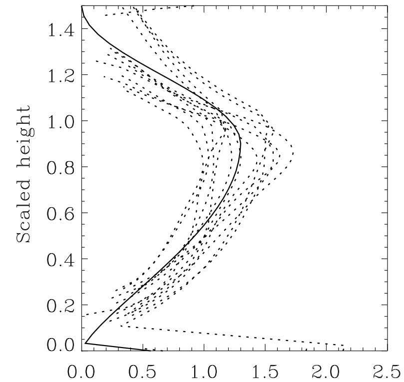

Figure 3: The shape function $f_V(z')$ diagnosed from LES using $\chi = q_t$. The solid line is the fit used in the SCM with $\Delta z_i = 0.5z_c$.

and dissipation arising from the cumulus elements:

$$l_s = \frac{\left((c_s e^{1/2})^3 + (c_s^{Cu} V f_V)^3\right)^{1/3}}{N_{BV}} \qquad (5)$$

where f_V is a shape function and V a velocity scale (notionally $e^{1/2}$ can be considered the relevant scale for unconditionally stable conditions, V for cumulus cloud layers). Note that here, both sets of coefficients c_s and c_s^{Cu} (different for momentum, heat and l_ϵ) use the formulations recommended by Mailhot and Lock (2004). Rearranging (3) allows K, and thence l_h, to be diagnosed from the LES. Similarly, the parametrization of ϵ can be rearranged to diagnose l_ϵ from LES data. Equation (5) can then be rearranged to allow Vf_V to be diagnosed from the LES in GL. In Fig. 3 this quantity is shown for l_h, scaled by $V = (w_*^3 + w^{*3})^{1/3}$. The collapse of the data is then very reasonable.

For unstable boundary layers, an analysis of SCM entrainment fluxes suggested that c_s should be a function of a bulk Richardson number, taking the smaller Mailhot and Lock values for weak inversions and the larger LH values for strong. Although this may point to a deficiency in, for example, the TKE transport, this simple Ri-dependence for c_s is used in the SCM in section 3.

2.4 Inversion depth

The height of the inversion base above the LCL can be diagnosed, as in Lock *et al.* (2000), from the model's thermodynamic profiles as the height of maximum buoyancy of a parcel lifted adiabatically (this parcel is also used to calculate the CAPE and thence w^*). In order to establish a realistic inversion structure in the model, it is necessary to parametrize, rather than diagnose, the inversion depth. This can be done using conservation of energy for updraughts impinging on the inversion. The domain mean energy scale for

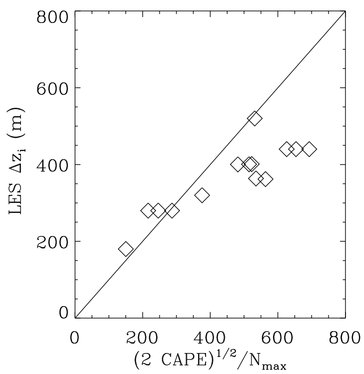

Figure 4: Inversion depth from the shallow cumulus LES in GL and the Sc/Cu LES plotted against the parametrization (6).

the cloud layer is assumed to be w^{*2} while $f_N(z' = 1) = 0.5$ so that the cloud area there, $N_i = 0.5 m_b / w^*$. Using the maximum N_{BV}, $N_{BV}^{\max}$, across the inversion as indicative of the stability encountered by rising parcels, the depth of the inversion is approximated by $\Delta z_i = (w^{*2}/N_i)/(\Delta z_i N_{BV}^{\max 2})$. Noting that $w^* = (m_b \text{CAPE})^{1/3}$, this gives

$$\Delta z_i = \frac{(2\text{CAPE})^{1/2}}{N_{BV}^{\max}} \tag{6}$$

This parametrization is found to work reasonably well against LES, see Fig. 4, although it tends to overestimate the inversion depth for the most strongly surface-forced simulations. However, these tend to be the LES which are not in perfect equilibrium so that the inversions may be somewhat smeared out, perhaps leading to an underestimate of $N_{BV}^{\max}$.

In the SCM, if (6) is found to give Δz_i thinner than three grid-levels a profile reconstruction technique is used, as coarse resolution grids may not measure $N_{BV}^{\max}$ accurately. Note that for stratocumulus-capped boundary layers, the CAPE would be expected to be small while $N_{BV}^{\max}$ will be large. Thus Δz_i would be small so that mixing in stratocumulus inversions will be dominated by the traditional TKE scheme.

3. SINGLE COLUMN MODEL RESULTS

This new non-local parametrization (hereafter NL) has been tested across a wide range of boundary layer regimes. Simulations in the stratocumulus limit show minor differences from parallel LH/BS simulations without the non-local terms, as expected. Cumulus simulations parallel to those from GL and the Sc/Cu LES accurately maintain the same low or high cloudiness equilibrium as the LES, reasonably independent of resolution (perhaps not surprisingly given the NL scheme was derived from their results), although the q_l profiles are also good. Here results will be shown only from the simulation of the diurnal cycle of shallow cumulus clouds over land that was used for intercomparisons in Brown *et al.* (2002) and Lenderink *et al.* (2004). An "operational" grid (around 200m away from the surface) and a constant 50m grid are used, with timesteps of 10 and 3 minutes, respectively.

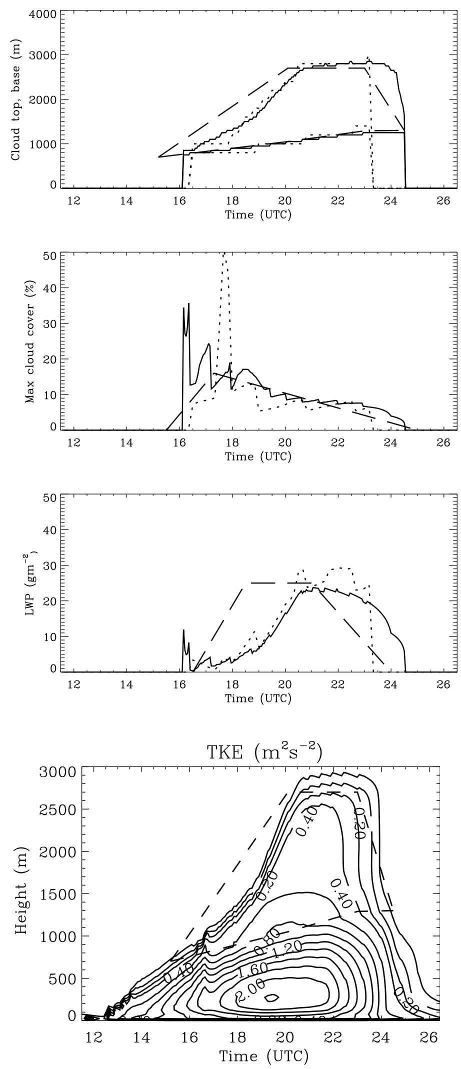

Figure 5: Time series from the SCM at 50m (solid) and operational (dotted) resolution and time-height section of TKE at 50m resolution. The dashed lines are approximate average results for the LES in Brown *et al.* .

Overall, the diurnal cycle is well represented (largely independent of resolution) with a gradual growth of the cloud layer and rise of cloud base, see Fig. 5. The cloud cover is good, reproducing the gradual decay through the day seen in the LES. The maximum cloud cover is at cloud-base, given by $N_0 = 2m_b/w^*$ in the NL scheme, which decreases as the CAPE and thence w^*

increases. There is some evidence of noise in the cloud fraction early on. In fact, this occurs as the top of the boundary layer rises across the grid-levels because the Gaussian part of the scheme is sensitive around the grid-scale saturation point. The LWP path is of the right magnitude but is underestimated early on and overestimated as the clouds in the LES decay. Associated with the cloud, there is a smooth evolution of the TKE profile, also in reasonable agreement with the LES which showed values in the cloud layer of 0.5 to 0.6 m^2s^{-2}.

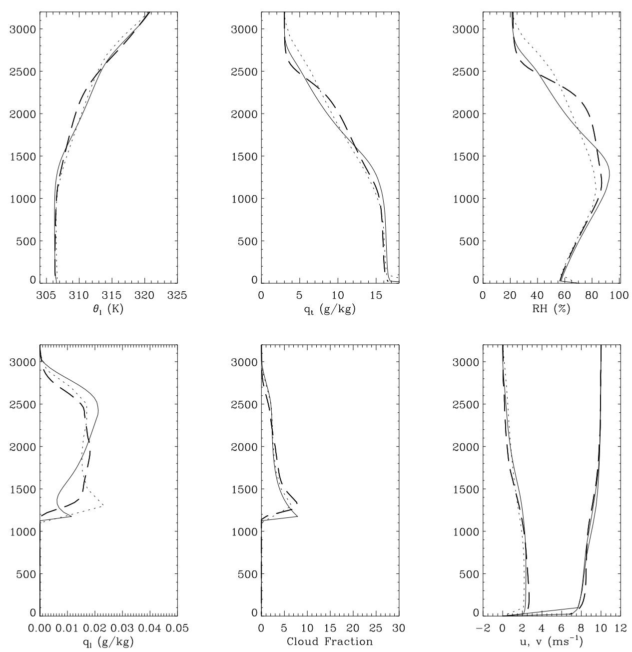

Figure 6: Profiles from the diurnal cumulus simulation at 2130Z, from the Met Office LES (dashed) and NL at 50m (solid) and operational (dotted) resolution.

As an example, Fig. 6 shows instantaneous profiles at 2130Z, the end of the growth phase. The cloud and wind fields show very good agreement with the LES. Compared to the SCM in Lenderink *et al.* , the thermodynamic fields are also quite reasonable, but these show a tendency to be too warm and dry in the upper part of the LES cloud layer and too cold and moist above, indicative of having mixed too deep. This problem appears to stem from the period between 19Z and 21Z, when the cloud top rose somewhat faster in the SCM compared to the LES (see Fig. 5). This difference is important because it is across the top of the cloud that the flux divergence leads to strong cooling and moistening. In summary, though, given that the NL scheme was developed from equilibrium LES, the performance is quite respectable.

4. SUMMARY

A new approach has been developed for boundary layer parametrization that combines a traditional Gaussian TKE closure with non-local functions to represent explicitly that part of the distribution arising from the more skewed cumulus elements. The non-local functions are scaled using the parameters developed for shallow cumulus convection by Grant and Brown. Single column model tests have demonstrated that the scheme works well across a broad range of cloudy boundary layers. Problems are still evident with the down-gradient diffusion parametrization for the transport term in the TKE budget which may well also require non-local terms. The pragmatic approach used here, of parametrizing the coefficient in the stable mixing length formulation, appears to work satisfactorily.

By basing the mixing length parametrization on that of Lenderink and Holtslag, the scheme benefits from their realistic sensitivity in near neutral boundary layers. The non-local part of the parametrization can readily and cheaply be added to a standard TKE closure scheme and testing in a NWP environment is underway.

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