An Eddy-diffusivity/Mass-flux Boundary Layer Parameterization Based on the TKE Equation: a Dry Convection Case Study

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ABSTRACT:
An eddy-diffusivity/mass-flux (EDMF) parameterization based on the turbulent kinetic energy equation (TKE) is proposed. The diffusive term is based on a prognostic TKE equation and the mass-flux term also depends on the prognostic TKE in two ways: in the initialization of a rising parcel, used for the estimation of updraft ensemble properties, and in the formulation of the mass-flux coefficient, which is proportional to the vertical velocity variance. The scheme is implemented in a one-dimensional version of the MesoNH model and tested for a dry convective boundary layer case, with realistic results. In particular, the EDMF-TKE closure is able to reproduce realistically the counter-gradient fluxes and the top-entrainment. The proposed parameterization is appealing because it leads to an integrated and unified approach to convective boundary layer parameterization, blending together concepts associated with eddy-diffusivity, mass-flux and the turbulent kinetic energy.
Key words: Sub-grid mixing, boundary layer, turbulent kinetic energy, turbulence and convection.

Una Parametrización de Flujo de Masa/Difusividad Turbulenta en Capa Límite basada en la Ecuación de la Energía Cinética Turbulenta: Caso de Estudio de Convección Seca

RESUMEN:
Se propone una parametrización de flujo de masa/difusividad turbulenta (EDMF) basada en la ecuación de la energía cinética turbulenta (TKE). El término difusivo se basa en una ecuación de pronóstico de la TKE y el término de flujo de masa también depende de la TKE pronosticada de dos modos: en la inicialización de una parcela ascendente, usada para la estimación de las propiedades medias de la corriente ascendente, y en la formulación del coeficiente de flujo de masa, que es proporcional a la varianza de la velocidad vertical. El esquema es implementado en una versión unidimensional del modelo MesonNH y verificado con un caso de capa límite convectiva seca, con resultados realistas. En particular el cierre EDMF-TKE es capaz de reproducir de manera realista los flujos contra-gradiente y el *entrainment* en la cima de la capa límite. La parametrización propuesta es interesante porque lleva a una aproximación integrada y unificada de la parametrización de la capa límite convectiva, combinando conceptos asociados con la difusividad turbulenta, el flujo de masa y la energía cinética turbulenta.
Palabras clave: mezca submalla, capa límite, energía cinética turbulenta, turbulencia y convección.

1. INTRODUCTION

The turbulent mixing of heat, moisture, momentum and trace gases plays an important role in determining the vertical structure of the atmosphere, affecting the surface weather conditions, and the dilution of the boundary layer (BL) air, hence the distribution of pollutants. The turbulent mixing in the convective BL is performed by eddies of different sizes, ranging from a few millimeters to large thermals with the BL height dimension, and their effect has been well documented either in observational field campaigns (Lenschow and Stephens 1980; Warner 1977) or in large-eddy simulation (LES) studies (Schumann and Moeng 1991; Siebesma and Cuijpers 1995; Brown et al. 2002).

In numerical weather prediction and climate models the turbulent and convective vertical transport in the boundary layer has to be parameterized because of computational efficiency reasons (i.e. the horizontal grid sizes are large when compared with the relevant boundary layer scales). Most global numerical weather prediction models still use first-order closures to parameterize these fluxes. In recent years, higher order turbulence closures have been used in mesoscale and global models, based on the turbulent kinetic energy equation (TKE) (Mellor and Yamada 1974; Sánchez et al. 2007). Both first order and TKE based closures are based on the concept of a mixing length, l, and require the computation of an eddy diffusivity, K, which in the latter schemes is a function of a prognostic TKE. Convective boundary layer mean profiles produced by prognostic TKE approaches are in general more realistic, because they take into account the vertical transport of TKE, than those simulated with first order closures, which assume a local balance between shear, buoyancy and TKE dissipation. It has been recently shown that TKE eddy-diffusivity approaches with simple mixing length formulations can realistically represent the top-entrainment in dry convective boundary layers (Teixeira and Cheinet 2004; Teixeira et al. 2004) as well as in cloud-topped boundary layers (Cheinet and Teixeira 2003). However, eddy-diffusivity approaches without any additional terms are unable to represent counter-gradient fluxes.

Observations show that in the upper half of the convective boundary layer the upward transport of heat is typically accompanied by a slightly stable mean potential temperature gradient, implying a counter-gradient heat flux. This counter-gradient mixing is due to convective plumes that dominate the transport in the convective boundary layer. Different counter-gradient approaches have been developed (Deardorff 1972; Holtslag and Moeng 1991), but the results are not necessarily satisfactory in the inversion region, because they do not correctly represent the top-entrainment (Siebesma and Teixeira 2000; Siebesma et al. 2007).

When moist convection is present in the convective boundary layer, global weather and climate prediction models often use an alternative parameterization for the cloud layer transport, namely a mass-flux approach, while the sub-cloud layer is still parameterized using eddy-diffusivity methods. It has been argued that this discontinuity in the type of parameterization may contribute to poor model results obtained for the cumulus topped boundary layer (e.g., Lenderink et al. 2004).

The mass-flux approach was introduced in the framework of cumulus convection (Arakawa 1969; Ooyama 1971; Betts 1973), as a result of observational evidence showing that the vertical transport is dominated by narrow cloudy updrafts (e.g., Warner 1977). In recent years, some mass-flux parameterizations have been applied to the dry convective boundary layer (e.g., Randall et al. 1992), pointing out that mass-flux schemes are well suited to parameterize the turbulent mixing due to thermals in the boundary layer.

Siebesma and Teixeira (2000) proposed a way of unifying the parameterization of the convective boundary layer, by combining eddy-diffusivity and mass-flux approaches, with a formulation based on similarity relations. The eddy-diffusivity/mass-flux (EDMF) approximation is intuitively based on the concept that small eddies perform local mixing that is parameterized by the eddy-diffusivity term, while the non-local mixing due to thermals is represented by the mass-flux term. This approach has been extended to shallow moist convection by Soares et al. (2004) and is discussed in detail in Siebesma et al. (2007). Additionally, the EDMF parameterization has been used to improve the vertical pollutant transport in the cumulus topped boundary layer by Angevine (2005).

In the present paper a new version of the EDMF approach is developed, taking the TKE budget equation as the main physical basis for its formulation. Both eddy-diffusivity and mass-flux contributions are linked to the TKE budget equation, using a 1.5 order turbulence closure that includes a non-local mixing effect, which represents the effect of strong updrafts in the boundary layer type of approach was introduced These are represented by a simple rising entraining parcel, and the mass-flux coefficient is proportional to the diagnosed variance of the vertical velocity. The new parameterization is implemented in the one-dimensional (single-column) version of the research model MesoNH (Lafore et al. 1996) taking advantage of the eddy-diffusivity closure of Bougeault and Lacarrère (1989) (BL89 hereafter). In the present study the one-dimensional (1D) version of the MesoNH model has the following mean prognostic variables: the two components of the horizontal wind, the turbulent kinetic energy e, the potential temperature θ and specific humidity q.

Section 2 of this paper presents the details of this version of the EDMF scheme. In Section 3, results from the 1D model with the EDMF parameterization are compared against results from a Large Eddy Simulation (LES) model and from the 1D model with the BL89 parameterization, for an idealized dry convective boundary layer case. The main conclusions are presented in section 4.

2. EDMF PARAMETERIZATION

If one defines an updraft with a fixed fractional area, a_u, that contains the strongest upward vertical velocities, it is possible to decompose, following Siebesma and Cuijpers (1995), the turbulent flux of a conserved variable, ϕ, into three terms, assuming that the vertical velocity in the surrounding environment is small $(w_e \approx 0)$:

$$\overline{w'\phi'} = a_u \overline{w'\phi'}^u + (1 - a_u)\, \overline{w'\phi'}^e + a_u w_u (\phi_u - \phi_e) \qquad (1)$$

where the *u* and *e* subscripts refer to the updraft and the environmental regions, and the over-bar represents a mean. Considering the following assumptions: 1) the fractional area covered with strong vertical motion is small, $a_u << 1$, which implies that the 1st term on the r.h.s. of (1) can be neglected; 2) $\phi_e \cong \bar{\phi}$, and, 3) the environmental turbulent flux (second term on the r.h.s.) is represented by an eddy-diffusivity closure; then the vertical mixing can be written as the sum of an eddy-diffusivity and a mass-flux contribution (Siebesma and Teixeira 2000):

$$\overline{w'\phi'} \cong - K \frac{\partial \bar{\phi}}{\partial z} + M\,(\phi_u - \bar{\phi}) \tag{2}$$

where $M\ 0\ q_u w_u$ is the mass-flux associated with the strong updrafts. This approach requires the specification of the eddy-diffusivity, *K*, the mass-flux, *M*, and the properties of the strong updrafts, ϕ_u.

Note that the EDMF approach is not used for the wind components and the vertical mixing of momentum follows the eddy-diffusivity approach of BL89.

A. EDDY-DIFFUSIVITY AND MASS-FLUX COEFFICIENTS

Siebesma and Teixeira (2000) utilized similarity approaches (e.g., Holtslag and Moeng 1991) to determine an eddy-diffusivity profile (*K*-profile) for heat and moisture. In order to provide a more general framework, in the present paper, the TKE balance equation is considered as the basis for the parameterization, and both *K* and *M* depend on this quantity.

The prognostic TKE equation, assuming an eddy-diffusivity approach for the vertical transport of TKE, may be written as

$$\frac{\partial e}{\partial t} = - \frac{1}{\rho_{ref}} \frac{\partial}{\partial z}(\rho_{ref}\,\overline{we}) - \overline{u_i'w'}\,\frac{\partial \bar{u}_i}{\partial z} + \frac{g}{\bar{\theta}_{vref}}\,\overline{w'\theta_v'} - \frac{1}{\rho_{ref}} \frac{\partial}{\partial z}\left(C_{2m}\rho_{ref} L e^{\frac{1}{2}} \frac{\partial e}{\partial z}\right) - C_\varepsilon \frac{e^{\frac{3}{2}}}{L}, \tag{3}$$

where ρ_{ref} and θ_{vref} are the reference state density and virtual potential temperature, respectively, *w* is the vertical velocity, *L* is the mixing length, and C_{2m} and C_ε are numerical constants for which Redelsperger and Sommeria (1981) proposed the values 0.2 and 0.7, respectively.

Following Cuxart et al. (2000), the eddy-diffusivity is proportional to a mixing length, a stability function and a velocity scale, which is the square root of the TKE:

$$K = \frac{2}{3} \frac{L}{C_s} e^{\frac{1}{2}} \phi_3, \tag{4}$$

where $c_s = 0.2$ and ϕ_3 is the stability function defined by Redelsperger and Sommeria (1981). The BL89 scheme is used to compute the mixing length at a given level as a function of the distance that a parcel of air, having the kinetic energy of the initial level, can travel upwards or downwards.

Siebesma and Teixeira (2000) showed that the mass-flux vertical profile in the convective boundary layer scales well with the standard deviation of the vertical velocity, σ_w, proposing $M = c\sigma_w$, with $c = 0.35$ and σ_w given by an empirical expression. Here, an alternative formulation is followed with the vertical velocity variance being diagnosed as a function of TKE (Cuxart et al. 2000):

$$\overline{w'^2} = \frac{2}{3}\, e - \frac{4}{15}\, \frac{L}{C_m}\, e^{\frac{1}{2}}\, \frac{\partial \bar{w}}{\partial z}, \tag{5}$$

where the constant $C_m = 4$. The mass-flux coefficient is given by $M = a_u \sqrt{\overline{w'^2}}$, where a_u is for simplicity taken as constant and equal to 0.3. In Soares et al. (2004) the mass-flux coefficient is function of the vertical velocity of the entraining ascent parcel.

To be consistent with the EDMF closure, the buoyancy production term in the TKE equation (3) is modified, to include a mass-flux contribution. Note that, as mentioned before, the transport term of TKE is not modified, since there are many uncertainties associated with it, including the definition of an updraft value for the TKE.

B. ASCENT MODEL

The ascent model for ϕ_u, describing the average properties of the ensemble of thermals, is now introduced. The strong updrafts are described by a rising entraining parcel, similar to the one used for cumulus convection (e.g. Betts 1973):

$$\frac{\partial \phi_u}{\partial z} = -\, \varepsilon \,(\phi_u - \bar{\phi}), \tag{6}$$

where ε is the fractional entrainment rate, that accounts for the lateral mixing of the surrounding air into the ascent. This rising parcel determines the vertical profiles of θ_u and q_u from lower boundary conditions.

In the absence of relevant observational data, we use Large Eddy Simulation (LES) results to assess these conditions. The numerical experiments use the Royal Netherlands Meteorological Institute (KNMI) LES model (e.g. Siebesma and Cuijpers 1995) to simulate an idealized dry convective boundary layer evolution, based on the case of Nieuwstadt et al. (1992), and include extensive diagnostics of the updrafts properties in the surface layer. The surface forcing corresponds to prescribed constant surface fluxes, $\overline{w'q'_s} = 2.5 \text{ x } 10^{-5}\ ms^{-1}$ and $\overline{w'\theta'_s} = 6.10^{-2}\ Kms^{-1}$. The initial profiles of potential temperature and humidity are:

$\theta = 300\ K,$ $\partial q_t/\partial t = -3.7 \times 10^{-4}\ km^{-1}$ $0 < z\ 1350\ m$

$\partial\theta/\partial z = 2\ K\ km^{-1},$ $\partial q_t/\partial t = -9.4 \times 10^{-4}\ km^{-1}$ $z > 1350\ m$

In the initial state the mean wind is negligible $(u, v) = (0.01,0)\ ms^{-1}$, allowing for a small but non-zero turbulent flux.

Following Troen and Mahrt (1986), the initial virtual potential temperature of the rising parcel in the surface layer is defined as $\theta_{vu}(z_k) = \bar{\theta}_v(z_k) + \Delta\theta_{vu}(z_k)$, where $\bar{\theta}_v$ is the mean value in the z_k level, and $\Delta\theta_{vu}$ is the excess, which scales with the ratio of the surface flux and a velocity scale. In the present work, TKE is used as the relevant velocity scale, while Siebesma and Teixeira (2000) used σ_w, with the Holtslag and Moeng (1991) empirical relation.

Fig. 1 shows the relationship between $\Delta\theta_{vu}(z_k)$ and $\overline{w'\theta'_{vs}}/e^{1/2}(z_k)$ diagnosed from LES experiments. It is clear that $\Delta\theta_{vu}(z_k)$ scales well with the ratio of the surface flux to $e^{1/2}$, independently of the chosen initial level, k, in the surface layer. Therefore it is assumed that

$$\theta_{vu}(zk) \cong \bar{\theta}_v(z_k) + \gamma\frac{\overline{w'\theta'_{vs}}}{e^{1/2}(z_k)}, \tag{7}$$

where the coefficient γ is adjusted to 0.3, as given by the best linear fit.

The vertical velocity of the updraft, w_u, is computed with the equation of Simpson and Wiggert (1969),

$$w_u\frac{\partial w_u}{\partial_z} = -\varepsilon\, bw_u^2 + aB, \tag{8}$$

with the buoyancy term $B = g(\theta_{v,u} - \bar{\theta}_v)/\bar{\theta}_v$ as a source term, a and b are coefficients to incorporate the pressure perturbations and the sub-plume turbulence terms (Siebesma et al. 2003). This equation is also used to estimate the inversion height z_i, which is set to be the level where w_u vanishes.

For moist convection, the parameterization of the entrainment rate has been historically based on plume models. Recently, however, Siebesma and Holtslag (1996) using LES results, obtained values of about $\varepsilon_1 = 2\text{x}10^{-3}\ \text{m}^{-1}$ for shallow convection, much smaller than those given by traditional plume models.

For the present case and for previous EDMF studies (e.g., Siebesma and Teixeira 2000; Soares et al. 2004), the fractional entrainment rate ε was also obtained from LES results, considering the dry convective boundary layer case previously described (Nieuwstadt et al. 1992). It was found that the profile ε is well fitted by:

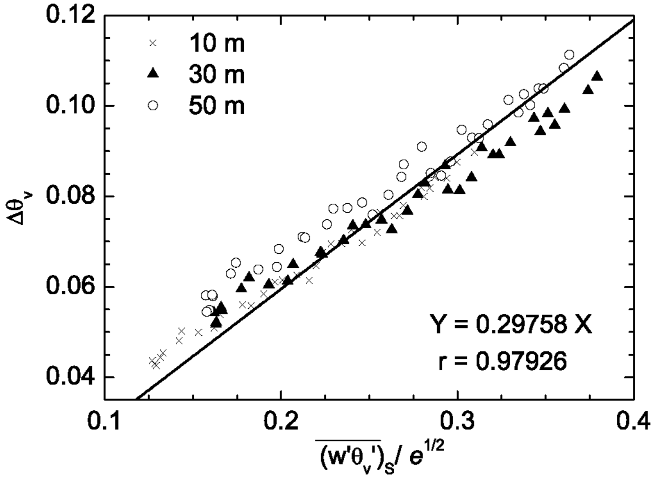

Figure 1.- Linear fitting between the updraft excess virtual potential temperature and the surface buoyancy flux, scaled by the square root of the TKE, for the three first model levels, as labeled.

$$\varepsilon = c_\varepsilon \left(\frac{1}{z} + \frac{1}{z - z_t} \right), \tag{9}$$

where $c_\varepsilon = 0.5$. For numerical reasons, to make the formulation independent of vertical resolution, it is considered that:

$$\varepsilon = c_\varepsilon \left(\frac{1}{z + \Delta z} + \frac{1}{(z - z_i) + \Delta z} \right), \tag{10}$$

The numerical integration uses a semi-implicit method, with a variable degree of implicitness with the mass-flux term included in the full solver of the tendency equations of the conserved variables.

3. EDMF RESULTS

This new version of the EDMF approach based on TKE is tested for an idealized dry convective boundary layer case, similar to the one described above. For this particular case, moisture is ignored and the surface forcing corresponds to a constant sensible heat flux of $\overline{w'\theta'_s} = 6.10^{-2}\ K\ ms^{-1}$. The initial profile of potential temperature corresponds to a stable profile with a lapse rate of $\partial q/\partial z = 2\ K\ km^{-1}$ down to 50m; below this level the potential temperature is constant and equal to its surface value (297.3 K). The vertical resolution of the one-dimensional EDMF model is 20m (as in the LES simulations) and the time step is 60 s. The EDMF model results are compared with LES results and with those obtained with the standard version of MesoNH, which uses an eddy-diffusivity approach based on BL89.

Fig. 2 shows hourly averaged profiles of $\bar{\theta}$ and θ_u at simulation hours 3, 5 and 7 from the EDMF model. The mean profiles present a typical dry convective boundary layer vertical structure: an unstable surface layer, a well-mixed layer and an upper stable layer. The updraft potential temperature structure looks realistic and compares well with LES output from previous simulations (Siebesma et al. 2007). The potential temperature excess is positive for most of the boundary layer decreasing from the surface to close to the boundary layer top where updrafts overshoot into the inversion. The capability of the EDMF model to represent the updraft properties is promising in terms of possible extensions to shallow moist convection boundary layer by adding saturation to the updraft equations. In fact, the dry thermals (represented on the average by the updraft potential temperature of Fig. 2) of the dry convective boundary layer can be thought of as the dry “roots” of shallow moist convection.

In Fig. 3, the hourly mean potential temperature profiles of the LES experiment, at the 4th and the 8th hours of simulation, are compared with the corresponding 1D simulation: BL89 and the new EDMF. The agreement between the LES profiles and the new scheme is quite good, and is clearly better than with the BL89 approach. Improvements are found throughout the profile, and a notable feature of the EDMF results is the good representation of the slightly stable upper half of the convective boundary layer, illustrating well that the mass-flux term is able to represent realistically the counter-gradient fluxes. The EDMF approach also produces a more realistic lower half of the boundary layer and a better representation of the top entrainment process.

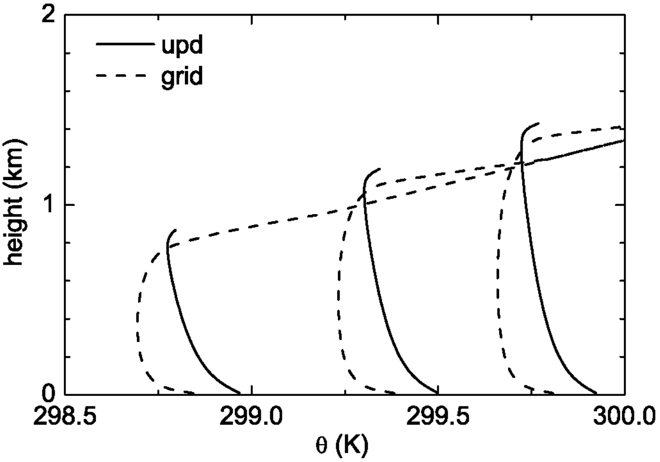

Figure 2.- Hourly averaged potential temperature (dashed lines), and updraft potential temperature at hours 3, 5 and 7obtained in 1D EDMF simulations.

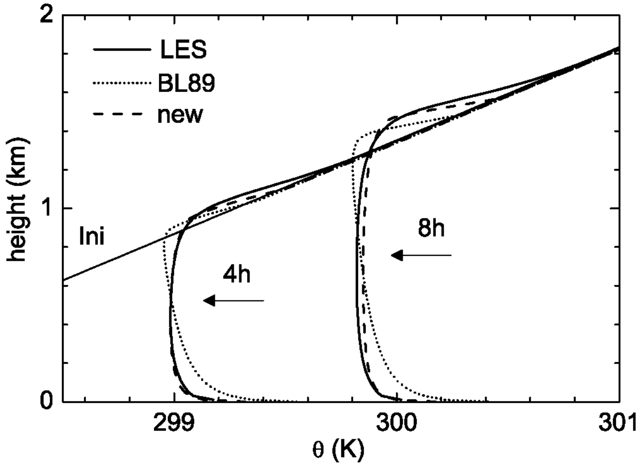

Figure 3.- Initial and hourly averaged potential temperature (K) profiles. Results from the new EDMF scheme (new), the BL89 scheme (BL89) and the KNMI LES are shown.

In order to have a better understanding of the performance of the new EDMF scheme, the buoyancy flux is presented in Fig. 4. This figure clearly shows an improvement with the EDMF parameterization in the top entrainment region, producing a precise prediction (as compared to LES) of the minimum buoyancy flux, and leading to a more realistic boundary layer evolution. As will be shown in more detail in Fig. 5, the better representation of the top entrainment is due to the mass-flux contribution, related to the overshooting of thermals (as depicted in Fig. 2). It is interesting to note (e.g. Teixeira and Cheinet 2004), that although eddy-diffusivity approaches can produce realistic

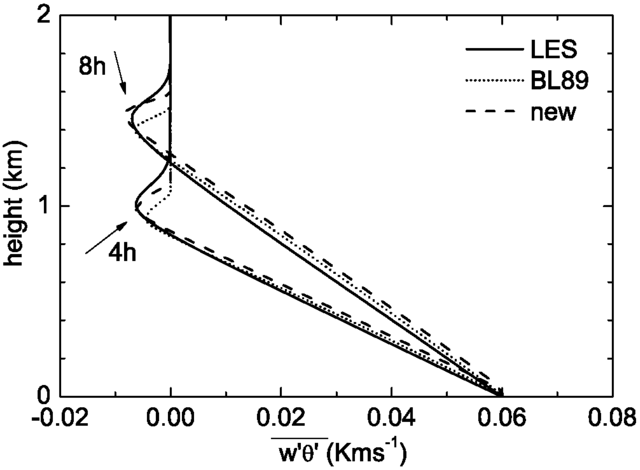

Figure 4.- As in Figure 3, but for the vertical flux of potential temperature *(Kms^{-1})*.

linear profiles of the heat flux (as shown in Fig. 4), the mean potential temperature profile adjusts itself (erroneously) in such a way as to produce the linear flux profile.

Fig. 5 shows the decomposition of the $\overline{w'\theta'}$ flux into the eddy-diffusivity and mass-flux terms (the two terms on the r.h.s. of (2)). The mass-flux term has a strong role on the negative top-entrainment flux that determines the boundary layer growth, in agreement with LES results that attribute much of the entrainment flux to non-local updrafts. Fig. 5 also shows the upward (counter-gradient) heat flux in the stable upper convective boundary layer, being maintained by the mass-flux contribution. On the other hand, the need for the eddy-diffusivity term is also illustrated in Fig. 5, showing its relevance close to the surface and the boundary layer top.

It has been well known for a long time (e.g., Ertel 1942; Deardorff 1966) that there is the need for a realistic representation of the counter-gradient heat transport in the convective boundary layer, associated with thermals. Different counter-gradient approaches have been developed (Deadorff 1972; Holtslag and Moeng 1991) but Siebesma and Teixeira (2000) and Siebesma et al. (2007) have shown that these approaches are not satisfactory in the inversion region, because they can lead to an incorrect representation of the top-entrainment. The EDMF approach is able to simulate realistically both processes: counter-gradient fluxes and top-entrainment.

Fig. 6 shows the evolution of the boundary layer height, diagnosed in the LES and in the 1D model with the BL89 and the EDMF parameterizations. The consequences of a less realistic representation of the top entrainment process in the BL89 approach are clear in this figure. The BL89 scheme after 8 hours of simulation produces an underestimation of the boundary layer height of about 200 *m*, while the EDMF results are in good agreement with the LES results.

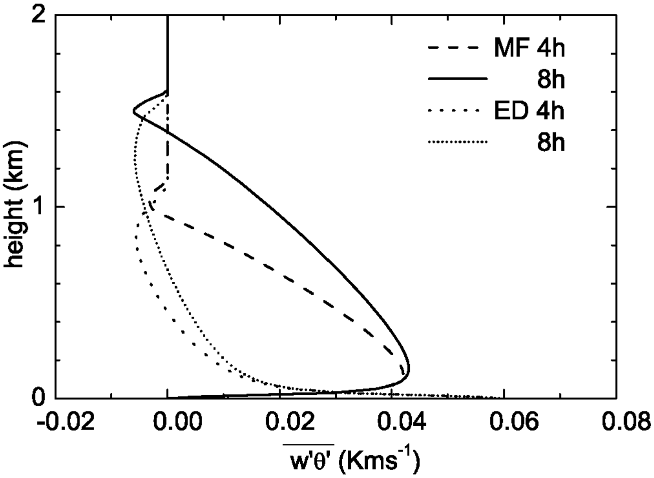

Figure 5.- Decomposition of the vertical flux of potential temperature into eddy-diffusivity (ED) and mass-flux (MF) contributions: hourly average results from the EDMF approach at hours 4 and 8.

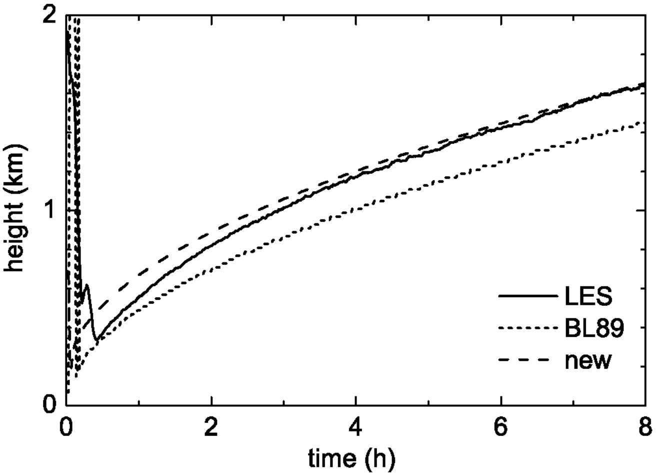

Figure 6.- Evolution of the inversion height (km). Results from the EDMF scheme (new), the BL89 scheme and the LES.

Nevertheless, the boundary layer height growth rate is similar for the BL89 and EDMF schemes.

The positive impact of taking in account the mass-flux contribution into the buoyancy flux term on the TKE equation, and hence in the vertical velocity variance, is revealed in Fig. 7, where it is shown that the EDMF approach is in better agreement with the LES than the BL89 approach, in both the maximum magnitude and the overall profile of the vertical velocity variance. The fact that EDMF leads to a maximum value of the vertical velocity variance close to the LES results is

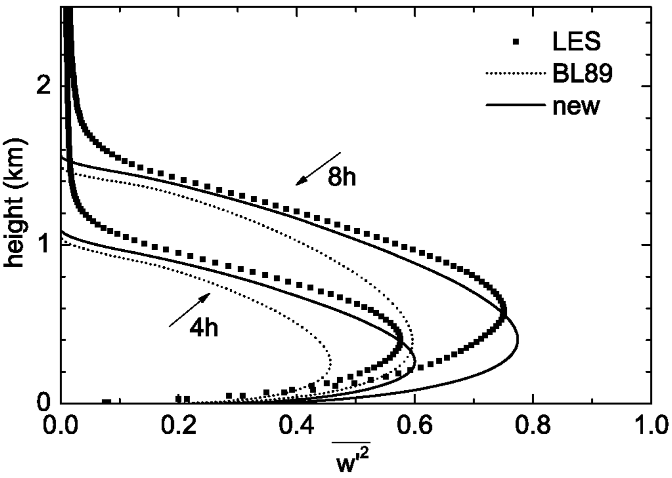

Figure 7.- Hourly averaged vertical velocity variance profiles. Results from the EDMF scheme (new), BL89, and LES.

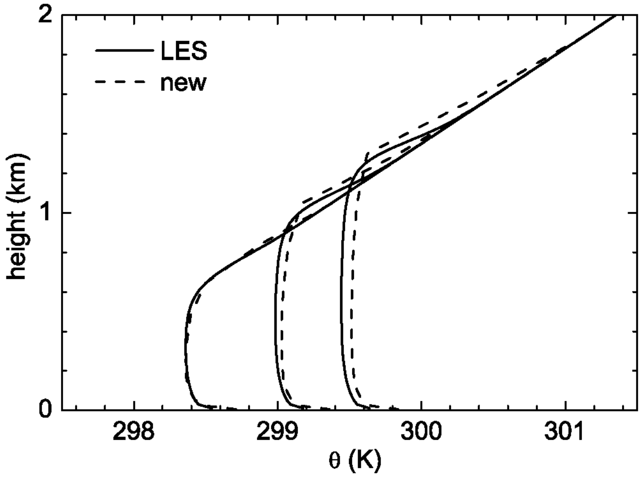

Figure 8.- Hourly averaged potential temperature profiles at hours 2, 4 and 6. Results from the KNMI LES, and from the new EDMF scheme (new) with a vertical resolution corresponding to the ECMWF model 40-level grid.

significant in terms of the capabilities of the EDMF parameterization in representing the turbulence characteristics of the dry convective boundary layer and in terms of possible extensions of the EDMF approach to shallow moist convection and to the cloud-topped boundary layer in general. Note again that the mass-flux term is parameterized as a function of the vertical velocity variance.

Global weather and climate prediction models typically have relatively low vertical resolutions. In order to study the sensitivity of the EDMF closure to the vertical resolution, the same case was simulated using the EDMF one-dimensional model with the vertical resolution of the ECMWF 40 and 60 level model, which has 12 levels below 1500 km height (see Teixeira 1999 for more details on the L40 and L60 ECMWF vertical resolution). In Fig. 8 the resulting θ vertical profiles are shown for the EDMF parameterization and the LES model, illustrating the fact that even with a relatively coarse vertical resolution, the EDMF model is able to produce a reasonable agreement with the LES output. There is, however, a slight overestimation of θ after 6 hours of simulation.

4. CONCLUSIONS

A realistic representation of the convective boundary layer is crucial for a diversity of applications from dispersion modeling to climate prediction and accurate forecasts of near surface meteorological parameters. In this paper, it has been shown that a unified approach using a simple combination of eddy-diffusivity and mass-flux (EDMF), both based on the TKE equation, can realistically describe the turbulent transport in the dry convective boundary layer. This approach differs from previous studies using EDMF methods in the sense that, by linking the eddy-diffusivity and mass-flux coefficients to the prognostic TKE, it leads to a more integrated and general approach, avoiding the use of empirical expressions, and giving a more consistent physical support to the different steps of the formulation.

This version of the EDMF scheme, implemented into the MesoNH model, produces realistic results for a dry convective boundary layer case study. The overall improvement of the boundary layer mean profiles is mainly due to the mass-flux contribution, allowing for a counter-gradient heat flux in the upper stable convective boundary layer and a better representation of the top entrainment, with the overshooting of thermals.

One important advantage of the EDMF approach is that it opens the way for unified parameterizations to represent shallow moist convection (and the cloud-topped boundary layer in general), by allowing for condensation in the updraft (e.g., Soares et al. 2004). In this context, the direct connection to TKE suggested and analyzed in this study can be seen as an important step in the quest for unified and integrated approaches for the parameterization of sub-grid turbulence and convection in weather and climate prediction models.

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