An integral approach for the representation of Turbulence, Convection and Clouds in weather and climate models

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Introduction

Notwithstanding the ever increasing computer resources, it is probably fair to state that most of the crucial processes in the clear and cloudy boundary layer will remain unresolved for both Numerical Weather Prediction (NWP) and climate models in the foreseeable future. Nevertheless, these unresolved processes, such as turbulence, convection, cloud dynamics and precipitation determine to a large extent the daily weather and climate conditions in which we live. It is therefore crucial to include these processes consistently in a parameterized way in both NWP and climate models and the design and implementation of such a coherent parameterization has been identified as a common key issue in both the climate and the weather research department of the KNMI. To bind expertise and to make optimal use of the limited resources at KNMI for model development, research efforts have been joint together in an internal project MESOMOD. The central aim of this project is the design of an integral approach for the representation of the most important sub-grid processes, namely turbulence, convection and cloud processes.

The term integral approach here refers to two issues. Firstly, the turbulence, convection and cloud parameterization are developed as one integral module. This will facilitate the exchange between different target models. Secondly, the physical parameterizations are tightly interlinked. Turbulence and convection are even described in one formulation in the so-called Eddy Diffusivity/Mass Flux (EDMF) approach[1, 2, 3]. Furthermore, convection and turbulence processes provide information on the subgrid variability of moisture that is used in a statistical cloud parameterization to estimate cloud cover and cloud water content. By applying an integral approach to all these processes, the interactions between clouds, convection and turbulence can be taken into account in a physical consistent manner.

The ultimate goal is to use this scheme operationally for both operational NWP and climate scenario purposes by implementing it in both the non-hydrostatic high resolution NWP model HARMONIE-MESO and in the regional atmospheric climate model RACMO. The latter activity is part of an externally funded project Climate Changes, Spatial Planning (CCSP). The initiative for this approach was initiated at ECMWF while the first author was working there as a consultant. Similar developments are being pursued at ECMWF and more recently also at Météo France for use in the French non-hydrostatic model AROME. It is for this reason that the development of this unified turbulence-convection-cloud scheme is done in close collaboration with these two institutes.

In the next two sections we highlight two recent model developments that contribute to the integral boundary layer scheme.

The Eddy Diffusivity Mass Flux (EDMF) approach

The traditional way to parameterize turbulent transport in the clear and cumulus topped boundary layer is to use an eddy-diffusivity approach for the clear boundary layer and the subcloud layer, whereas an advective mass flux approach is used for the convective transport in the cumulus cloud layer. This rather ad-hoc split up has led to numerous problems such as double counting of transport processes and unrealistic transitions between the clear and cloudy boundary layer. Moreover, the use of a simple eddy-diffusivity approach in the clear boundary layer has been criticized for decades because it merely assumes turbulent transport to be down-gradient. Therefore this method is unable to describe non-local mixing in the upper part of the convective boundary layer, where often a slightly stable potential temperature profile is observed.

In order to overcome these drawbacks a new method has been proposed that combines the advective mass-flux approach and the eddy-diffusivity method in a coherent way, so that it paves the way for a unified parameterization of turbulent transport in the cloud topped boundary layer. The whole concept is based on a separate treatment of the organized strong updrafts and the remaining turbulent field. The non-local updrafts are described by an advective mass-flux approach whereas the remaining turbulent part is represented by an eddy-diffusivity approach

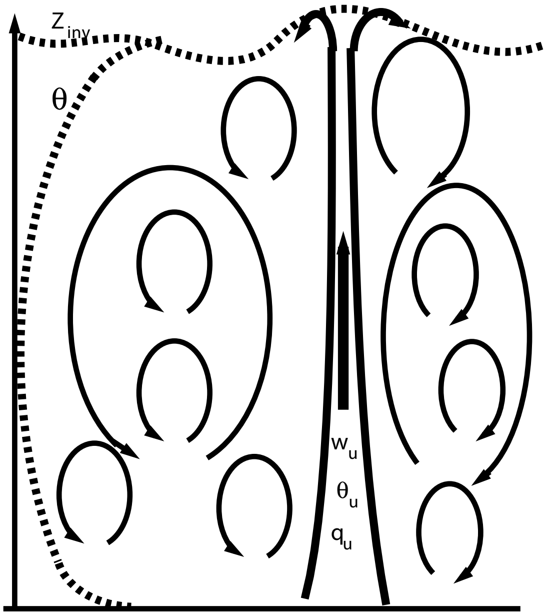

Figure 1. Sketch of a convective updraft embedded in a turbulent eddy structure.

(see Figure 1). The basic idea has been formulated in[1, 3] and practical applications of this approach to the cloud topped boundary layer have been discussed in[2].

In short, by assuming that strong updrafts occupy only a small spatial fraction, it can be derived that the turbulent flux of any conserved variable ϕ , can be well approximated by

$$\overline{w'\phi'} \approx -K\frac{\partial\overline{\phi}}{\partial z} + M\left(\phi_u - \overline{\phi}\right)$$

where the subscript u refers to the strong updrafts, overbars denote a spatial average, primes deviations from this average, K the eddy diffusivity. The mass flux is defined as $M \equiv a_u\left(w_u - \overline{w}\right)$, i.e. the product of the updraft velocity and the updraft area a_u . The first term on the right hand site describes the small scale turbulence while the second term, i.e. mass flux term, describes the non-local organized transport due to the strong updrafts. It should be noted that this mass flux term will be active in both the clear and the cloudy boundary layer case so that a continuous transition between the clear and cloudy boundary layer is possible and a triggering mechanism for the onset of cumulus convection is not necessary anymore. Moreover, in clear conditions the mass flux term describes the countergradient transport and is able to create a realistic slightly stable temperature profile in the upper part of the convective boundary layer.

Finally we need to obtain coefficients for the eddy-diffusivity K, the mass-flux M and a model for the updraft fields ϕ_u. Although the optimal choice of these coefficients is still an active field of research, simple assumed profiles for the eddy diffusivity K and the mass flux M already give surprisingly good results. As a demonstration Figure 2a compares the development of the boundary layer height parameterized by the EDMF scheme with Large Eddy Simulation (LES)

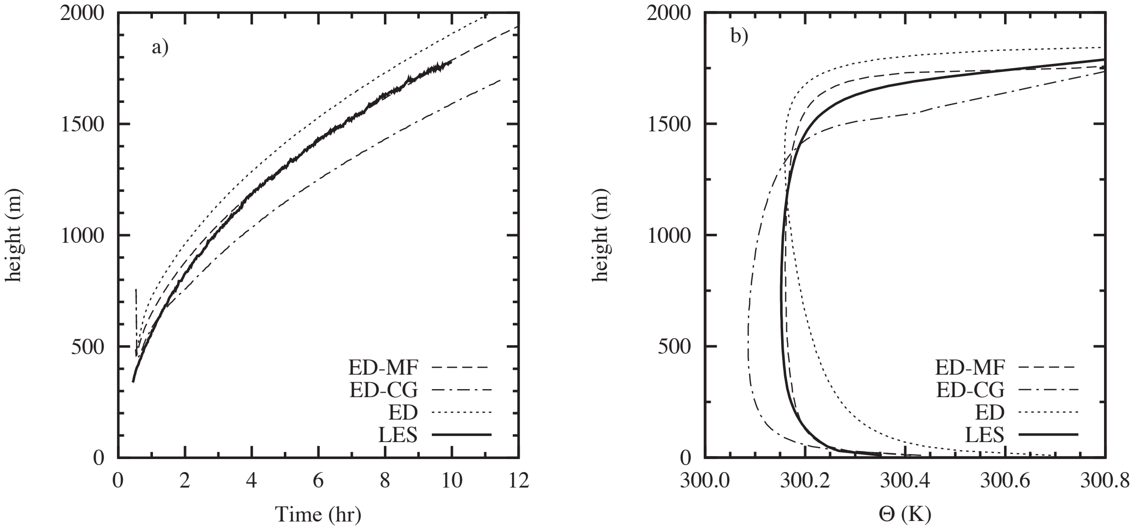

Figure 2. a) Boundary layer growth determined by: the single Eddy-Diffusivity approach (dotted), Eddy-Diffusivity combined with a countergradient term (dash-dotted) and by the EDMF approach along with the LES results as a reference. b) The mean potential temperature profile after 10 h of simulation for all three approaches.

> *The whole concept is based on a separate treatment of the organized strong updrafts and the remaining turbulent field*

model results. It shows superior behaviour when compared with the traditional eddy diffusivity (ED) approach or with the eddy-diffusivity-countergradient (EDCG) method. Moreover Figure 2b shows that the temperature profile structure is also best represented by the EDMF method. For a further physical explanation of this performance we refer to the literature[3)].

A simple parameterization for detrainment in shallow cumulus[4)]

Virtually all shallow cumulus convection parameterizations use a mass flux concept. Within the mass flux framework the upward mass transport is usually described by a simple budget equation

$$\frac{\partial M}{\partial z} = (\varepsilon - \delta)M$$

where M denotes the upward mass flux, the fractional entrainment coefficient ε describes the inflow of environmental air into the cloudy updraft while the fractional detrainment δ describes the outflow of cloudy air into the environment. Recently there has been renewed interest in the parameterization of especially the fractional entrainment rate. However, little attention has been paid to the parameterization of the detrainment process although this counterpart of the cloud mixing process is, as this study shows, even more important for obtaining realistic mass flux profiles in cumulus convection.

The most simple and still widely applied description of lateral mixing in a mass flux concept is the use of fixed fractional entrainment and detrainment rates. With ‘fixed’ we mean constant values or some fixed function with height. Siebesma and Holtslag[5)] demonstrated that well-chosen constant detrainment and entrainment rates are adequate for the relatively simple steady-state BOMEX shallow convection case[6)]. However, Single Column Model (SCM) results with the same fixed ε and δ for the more complex ARM case[7)], with varying cloud depths and environmental conditions, reveal large discrepancies with LES results. To explain these differences between the LES model and SCM, we analyze the lateral exchange in the LES model for three different shallow convection cases.

The LES results show that from hour to hour and case to case, the fractional entrainment rate shows little variation and it can be demonstrated that one fixed function, namely $\varepsilon = 1/z$[8)] performs very well for a wide range of conditions (see Figure 3a for the complex

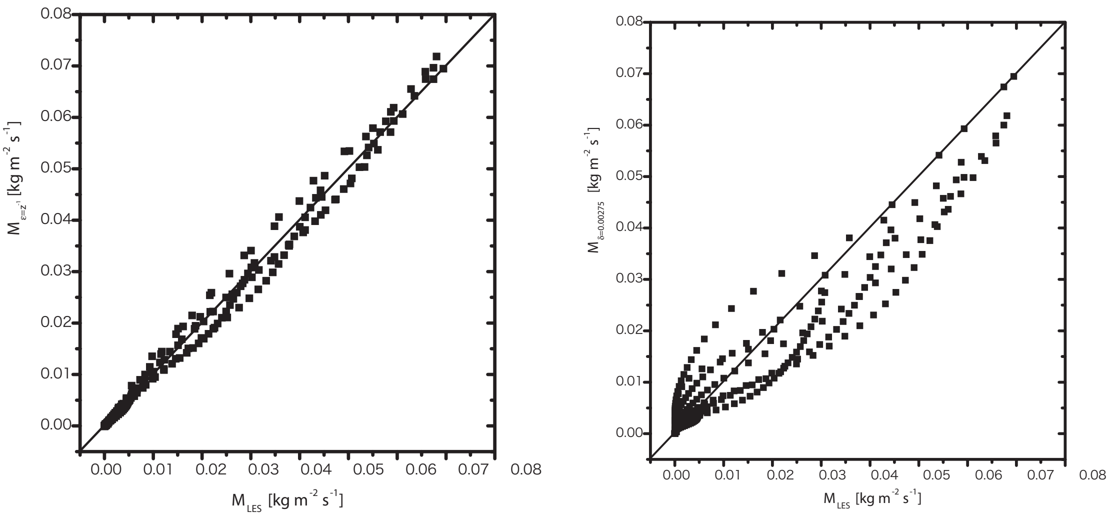

Figure 3. Comparison of the mass flux M for the ARM case[7)] as directly diagnosed from LES with (a) the mass flux obtained using a fixed $\varepsilon = 1/z$ along with the dynamical LES diagnosed δ or (b) with the mass flux obtained using $\delta = 2.75\cdot10^{-3}$ m along with the dynamical LES diagnosed ε.

ARM case). We therefore adopt this fixed function for ε in our parameterization. On the other hand LES results also reveal much more variation in the fractional detrainment rate with a strong influence on the mass flux profile (see Figure 3b). The value of δ seems to depend mainly on two factors. Firstly, δ depends on the cloud layer depth. Under normal conditions a shallow convection scheme in a NWP or climate model represents an ensemble of clouds, leading to a decreasing mass flux profile with height and zero mass flux at the top of the cloud layer[9]. However, if we apply fixed fractional entrainment and detrainment rates we also fix the mass loss per meter. Figure 4 shows how fixed rates based on the BOMEX case (with a cloud layer depth of 1000m) lead to a non-zero mass flux at cloud top for a shallower cloud layer while applying these rates on a deeper cloud layer result in an almost zero mass flux already halfway the cloud layer, all in disagreement with the cloud ensemble and LES. With an approximately fixed function for the entrainment coefficient it can be simply understood that this calls for smaller detrainment rates for deeper cloud layers, as also confirmed by LES. Nevertheless, current mass flux schemes ignore this cloud layer height dependence, evidently leading to erroneous mass flux profiles. In our approach the mass flux profile is considered in a non-dimensionalized way, therewith dealing with the effect of the cloud layer height.

The second important factor changing δ is the environmental condition. Many studies (see e.g.[10]) showed the influence of the relative humidity of the environmental air surrounding the updrafts. If the surrounding air is moister, less evaporative cooling will occur if this air is mixed with cloudy air and this leads to less detrainment. However, besides the humidity of the environment also the buoyancy excess of the updraft air determines whether the mixture becomes negatively buoyant and consequently detrains. This combined effect is nicely captured by the so-called critical fraction χ_c of the environmental air[10]. This parameter is defined as the fraction of environmental air that is needed to make a mixture of environmental and updraft air neutrally buoyant. Figure 5 reveals how in our approach χ_c is used in a bulk sense to describe the effect of environmental conditions on the non-dimensionalized mass flux profile and therewith on the fractional detrainment rate. With this distinct relation based on LES for three different shallow convection cases, our detrainment parameterization is closed.

> *Current mass flux schemes ignore this cloud layer height dependence, evidently leading to erroneous mass flux profiles*

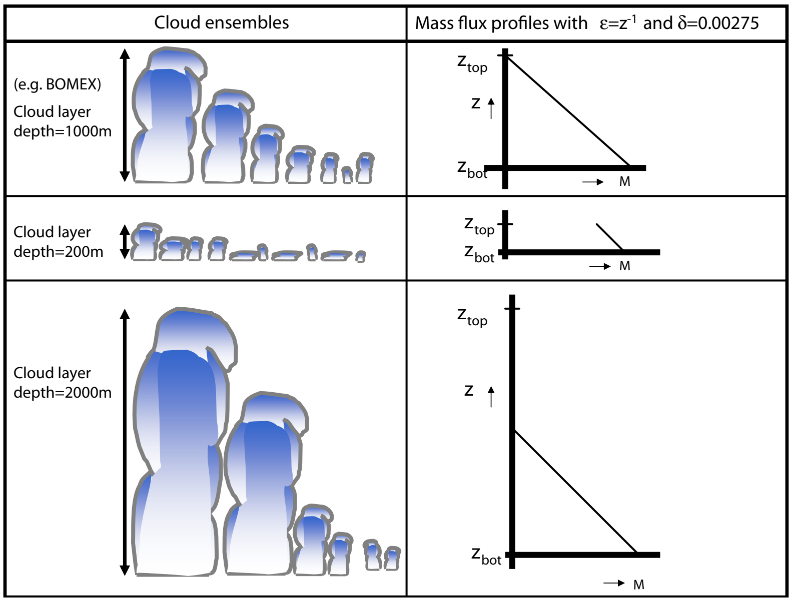

Figure 4. Cloud ensembles for different cloud layer depths and the corresponding mass flux profiles using fixed ε and δ based on a cloud layer depth of 1000m (BOMEX[6]).

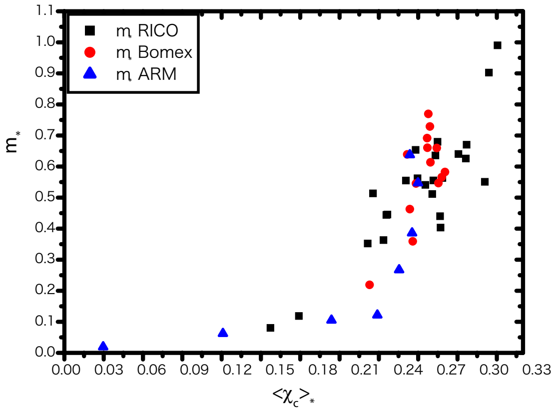

Figure 5. LES results showing for three different shallow convection cases the relation between m_* and $\langle\chi_c\rangle_*$, where m_* is the non-dimensionalized mass flux (M/Mb where Mb is the cloud base mass flux) half way the cloud layer, and $\langle\chi_c\rangle_*$ is χ_c (see text) averaged over the corresponding layer, i.e. the lower half of the cloud layer.

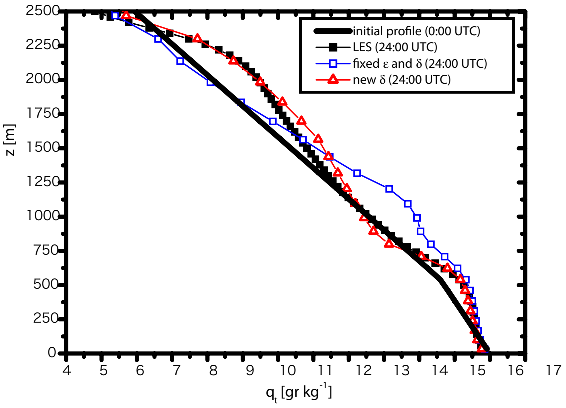

Figure 6. Total water specific humidity profiles after 24 hrs of simulation during the RICO *case11) for the* LES *model and for the* SCM *using fixed ε and δ or the new detrainment parameterization.*

Results with the new parameterization in a Hirlam SCM for a wide range of shallow cumulus convection cases (BOMEX6)), ARM7) and RICO11)) illustrate the strength of this new detrainment parameterization. As an example, we show in Figure 6 the total specific humidity profile of the RICO case after 24 hours of simulation. Presented are the results of an LES model, a SCM with fixed fractional entrainment and detrainment coefficients as known from literature (based on LES results for BOMEX), and finally a SCM with the new detrainment parameterization. The new parameterization gives an almost perfect match with the LES humidity profile. There is also a large improvement on the results with fixed entrainment and detrainment coefficients which can be explained by the relatively deep cloud layer and favourable conditions for updrafts during the RICO case which leads to relatively small fractional detrainment values and thus strong convection.

Results from LES and SCM show clearly the potential of our approach for a wide range of shallow convection cases. The new parameterization can be seen as a robust alternative for more complex buoyancy sorting based convection schemes without some of the disadvantages. Moreover, the new parameterization is computationally cheap and can be easily included in existing mass flux schemes.

Conclusions and outlook

A unified and integral parameterization approach is essential for the description of the clear and cloudy boundary layer. The EDMF approach presented here provides an excellent framework to accomplish this. Within this framework a number of processes still need to be further parameterized. For example, for the convective transport in the cloud layer, a realistic representation of the mass flux is crucial and it is predominantly determined by the detrainment rate. The new developed detrainment parameterization presented above, is therefore an important step to the application of the EDMF approach in operational climate and NWP models.

Within MESOMOD and in international cooperation we are developing and evaluating the various EDMF components12, 13). Perhaps the most important hurdle that has to be tackled at this moment is the use of a Turbulent Kinetic Energy (TKE) scheme for the Eddy Diffusivity part and its interaction with the mass flux component.

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