P1.6 AN INTEGRATED TURBULENCE SCHEME FOR BOUNDARY LAYERS WITH SHALLOW CUMULUS APPLIED TO POLLUTANT TRANSPORT

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1. INTRODUCTION

This presentation describes a scheme which provides an integrated description of turbulent transport in free-convective boundary layers with shallow cumulus. The scheme uses a mass-flux formulation, as commonly found in cumulus schemes, and an eddy diffusivity. It is called "mass flux - diffusion" or "M-K" for short. Both components are active in both the subcloud and cloud layers. Results of simulations of the ARM 21 June 1997 case, which has been used for other model intercomparisons (Brown et al. 2001; Lenderink et al. 2004) will be shown.

The motivation to work on this problem comes from its importance for atmospheric chemistry and regional air quality applications. Models without cumulus will produce incorrect profiles of chemical constituents, whether those constituents are emitted at the surface or transported aloft. The scheme's ability to simulate the profile of a conserved scalar is applied to a case from the 1999 Southern Oxidants Study Nashville experiment, where it is used to simulate vertical profiles of carbon monoxide in a cloud-topped boundary layer.

Siebesma and Teixeira (2000) introduced the idea of an integrated scheme for turbulent vertical transport in cloud-topped convective boundary layers, which they called an "advection-diffusion" scheme. Variations of this idea have been presented by Soares et al. (2004) and Jakob and Siebesma (2003). The scheme presented here owes a great deal to their work, but differs at some points.

Brevity precludes going into detail of the extensive history and taxonomy of turbulence schemes for the dry boundary layer here. The reader may refer to the standard textbooks. Dry boundary layer schemes fall into two basic categories, local and non-local. Local schemes are based on an analogy to molecular diffusion. Non-local schemes are based on the observation that most of the energy in convective boundary layers is carried by structures ("large eddies") whose size is comparable to the depth of the layer, and therefore much larger than the model grid spacing. Local schemes may be modified by various means to allow for the observed counter-gradient transport. In the absence of such modifications, local schemes produce simulated profiles with unrealistic gradients (Lock et al. 2000).

Schemes for shallow convection are reviewed by Siebesma (1998). The standard approach involves the definition of an updraft carrying a certain amount of mass and having specific properties (temperature, water vapor content, etc.), and therefore is called the mass-flux approach. The updraft mass flux and properties are modified by lateral entrainment and detrainment (not to be confused with vertical entrainment at the top of the dry boundary layer). The entrainment and detrainment rate profiles are the critical elements of mass-flux schemes.

Extending the mass-flux approach downward into the subcloud layer provides a non-local transport component in that layer, eliminating the need for other counter-gradient correction terms. The mass-flux term alone, however, is not adequate as the only representation of turbulence in the subcloud layer. Petersen et al. (1998) show that the mass-flux component is about two-thirds of the total flux in such a layer. The remainder can be thought of as the results of smaller-scale ("subgrid") transport and is therefore appropriately represented by a local scheme such as eddy diffusion.

The need for a local turbulence component in the cloud layer is less clear. When the cloud fraction is very small, turbulence outside the clouds should be negligible. A potential barrier exists betwen the subcloud layer and the cloud layer, and the profile of turbulence intensity has two maxima (Siebesma 1998). Only the most energetic updrafts can overcome the potential barrier and form clouds, and all of the transport through cloud base is by these strongest updrafts. As the cloud fraction approaches 100%, the cloud would be considered stratocumulus, the distinction between cloud and subcloud layers disappears, there is no potential barrier, and the profile of turbulence intensity has

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only a single maximum. Intermediate cases should require both local and non-local transport in varying proportions depending on the cloud fraction, or equivalently on the strength of the potential barrier between the two layers.

If one uses separate boundary layer (subcloud) and cumulus schemes, the closure assumption at cloud base is a difficult question (Siebesma and Holtslag 1996). In the M-K scheme, we simply assume that the mass flux is continuous across the cloud base. This is equivalent to assuming that the strongest updrafts are those that form clouds, which is precisely the basic idea of this scheme.

Several related approaches have appeared in the literature. Wang and Albrecht (1990) used a mass-flux parameterization in the dry boundary layer. Lappen and Randall (2001a,b,c) developed a parameterization for both the dry and moist convective PBL. Their approach combines mass-flux and higher-order closure, and uses assumed probability distributions. They also provide a review of previous similar work. Assumed probability density functions also underlie the work of Golaz et al. (2002). De Roode et al (2000) argue that mass-flux and (more common) Reynolds-averaged formulations are to some degree equivalent.

Previous work on chemical transport by clouds was reported by Lin et al. (1994). They incorporated a parameterization of subgrid convective cloud transport into a 3D regional chemistry model, and compared the results with aircraft observations. The primary emphasis was on deep convective cloud. Because of the relatively coarse vertical grid spacing in their model, they used a very simple representation of shallow cloud. However, their figure 7 shows some impact on the chemical profiles from the shallow cloud vertical transport.

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References:

Brown, A.R., and coauthors, 2001: Large-eddy simulation of the diurnal cycle of shallow cumulus convection over land. *Q.J. Royal Met. Soc.*, **127**, 1-19.

DeRoode, S.R., P.G. Duynkerke, and A.P. Siebesma, 2000: Analogies between mass-flux and Reynolds-averaged equations. *J. Atmos. Sci.*, **57**, 1585-1598.

Golaz, J.-C., V.E. Larson, and W.R. Cotton, 2002: A PDF-based model for boundary layer clouds. Part I: Method and model description. *J. Atmos. Sci.*, **59**, 3540-3551.

Jakob, C., and A.P. Siebesma, 2003: A new subcloud model for mass-flux convection schemes: Influence on triggering, updraft properties, and model climate. *Monthly Weather Review*, **131**, 2765-2778.

Lappen, C.-L., and D.A. Randall, 2001a: Toward a unified parameterization of the boundary layer and moist convection. Part I: A new type of mass-flux model. *J. Atmos. Sci.*, **58**, 2021-2036.

Lappen, C.-L., and D.A. Randall, 2001b: Toward a unified parameterization of the boundary layer and moist convection. Part II: Lateral mass exchanges and subplume-scale fluxes. *J. Atmos. Sci.*, **58**, 2037-2051.

Lappen, C.-L., and D.A. Randall, 2001c: Toward a unified parameterization of the boundary layer and moist convection. Part III: Simulations of clear and cloudy convection. *J. Atmos. Sci.*, **58**,2052-2072.

Lenderink, G., and coauthors, 2004: The diurnal cycle of shallow cumulus clouds over land: A single column model intercomparison study. *Q.J.R. Meteorol. Soc.*, submitted.

Lenderink, G., and A.A.M. Holtslag, 2004: An updated length scale formuation for turbulent mixing in clear and cloudy boundary layers. *Q.J.R. Meteorol. Soc.*, submitted.

Lin, X., B.A. Ridley, J. Walega, G.F. Hübler, S.A. McKeen, E.-Y. Hsie, M. Trainer, F.C. Fehsenfeld, and S.C. Liu, 1994: Parameterization of subgrid scale convective cloud transport in a mesoscale regional chemistry model. *J. Geophys. Res.*, **99**, 25,615-25630.

Lock., A.P., A.R. Brown, M.R. Bush, G.M. Martin, and R.N.B. Smith, 2000: A new boundary layer mixing scheme. Part I: Scheme description and single-column model tests. *Monthly Weather Review*, **128**, 3187-3199.

Siebesma, A.P., and A.A.M. Holtslag, 1996: Model impacts of entrainment and detrainment rates in shallow cumulus convection. J. Atmos. Sci., 53, 2354-2364.

Siebesma, A.P., and J. Teixeira, 2000: An advection-diffusion scheme for the convective boundary layer: Description and 1D-results. *Proceedings, 14th Symposium on Boundary Layers and Turbulence*, Aspen, Colorado, 7-11 August 2000.

Siebesma, A.P., 1998: Shallow cumulus convection. In *Buoyant Convection in Geophysical Flows*, E.J. Plate, E.E. Fedorovich, X.V. Viegas, and J.C. Wyngaard eds., Kluwer Acad., pp. 441-486.

Soares, P.M.M., P.M.A. Miranda, A.P. Siebesma, and J. Teixeira, 2004: An eddy-diffusivity/mass-flux parametrization for dry and shallow cumulus convection. *Q.J.R. Meteorol. Soc.*, submitted.

Teixeira, J., and S. Cheinet, 2004: A simple mixing length formulation for the eddy-diffusivity parameterization of dry convection. *Bound.-Layer Meteorol.*, **110**, 435-453.