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An Updated Length Scale Formulation for Turbulent Mixing in Clear and Cloudy Boundary Layers

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Summary

A new mixing length scale is presented for turbulence closure schemes with special emphasis on neutral to convective conditions in clear and cloudy boundary layers. The length scale is intended for a prognostic turbulent kinetic energy closure. It is argued that present-day length scale formulations may easily fail in one of following limits: schemes based on a local stability measure (e.g., the Richardson number) display unrealistic behavior and instabilities in the convective limit. This strongly limits the representation of mixing in cloudy boundary layers. On the other hand, it is shown that non-local parcel methods may misrepresent mixing near the surface. The new length scale formulation combines local and nonlocal stability in a new way; it uses vertical integrals over the stability (the Richardson number) in a simple "parcel" framework. The length scale matches with surface layer similarity for near-neutral conditions and displays a realistic convective limit. The use of the length scale formulation can be extended well to cloudy boundary layers. The scheme is numerically stable and computationally cheap. The behavior of the length scale is evaluated in a Single Column Model (SCM) and in a high resolution Limited Area Model (LAM). The SCM shows good behavior in three cases with and without boundary layer clouds. The prediction of the near surface wind and temperature in the LAM compares favourably with tower measurements at Cabauw (the Netherlands).

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1. Introduction

Higher order turbulence closures in weather prediction and climate model are receiving increasing attention (e.g., Therry and Lacarrere 1983; Bougeault and Lacarrère 1989; Bélair *et al.* 1999; Cuxart *et al.* 2000; Grenier and Bretherton 2001; Abdella and McFarlane 2001; Lenderink and Holtslag 2000). The simplest version (which is relatively cheap in computational demands) is a TKE-l scheme, which combines a prognostic equation of Turbulent Kinetic Energy (TKE or E) with a diagnostic length scale $l_{m,h}$ to compute the eddy diffusivity for momentum and heat.

Despite the more advanced physics introduced by the higher order TKE equation, it is still not well understood how to model the corresponding length scale, and proposals combine rather ad-hoc arguments (often based on matching) and/or simple physical concepts. For example, in the ECHAM4 scheme the length scale is chosen such that the TKE scheme matches with the Louis scheme near the surface. The main reasons for that ad-hoc matching procedure is that i) the Louis scheme yields sufficiently realistic behavior close to the surface (Beljaars and Holtslag 1991), and ii) the Louis scheme can be well adjusted (tuned) to the needs of operational models (e.g., Beljaars and Viterbo 1998). However, Lenderink *et al.* (2000) showed that the ECHAM4 TKE scheme displays large instabilities in an idealized case of Stratocumulus, caused by the interaction between the cloud physics and the length scale formulation, which is to a large extend based on the local Richardson number (see Section 2 for details). The strong dependency of turbulent mixing on local stability may amplify noise on a grid point level,

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eventually leading to numerical instability. The generation of noise by turbulence schemes is a rather general problem in cloudy boundary layers (see e.g. Lenderink *et al.* 2004, in this issue).

Besides the numerical disadvantage of a strong dependency of the length scale on local stability, the physics behind this concept might also be questioned. In unstable conditions, the length scale at a certain height is constrained by the size of largest eddies; close to inversion, the length scale should therefore be limited by the presence of the inversion. In ECHAM4 the length scale only "feels" changes in local stability; there is no clear non-local control of the length scale.

A natural way to incorporate non-local stability into the length scale is proposed by Bougeault and Lacarrère (1989) (hereafter B&L). In this method, the length scale is computed from the distances which an upward and a downward adiabatic parcel can travel before being stopped at a level where it has lost all its kinetic energy by buoyancy effects. In this way, the stability of a whole layer is incorporated into the length scale. This method is physically appealing since it is based on the simple concept that the major part of transport is done by the largest eddies. The scheme has been tested extensively in convective boundary layers with good results. However, since mainly buoyancy enters the B&L length scale formulation, it will not react strongly to changes in the wind shear. With a usual TKE scheme this may easily give rise to conflicts with surface layer scaling for neutral to convective conditions (see Section 2).

Summarizing, the B&L length scale for unstable conditions is in a sense extremely non-local. It is mainly determined by the boundaries of the mixing domain. The scheme appears to have problems in reflecting a proper surface layer scaling for neutral to convective conditions. On the other extreme, the ECHAM4 length scale formulation is extremely local. This scheme has rather good surface layer characteristics, but also suffers from instability higher up in the atmosphere. The matter of local versus non-local impacts on the mixing coefficient has been put forward by Delage (1997) and has also been studied in a TKE scheme by Bélair *et al.* (1999): To what extend should local and non-local stability characteristics enter the K (or length scale) formulation? In the following we will use the term local and non-local always in this sense. (In literature, non-local is frequently used to denote non-local transport other than local K-diffusion; see e.g., Deardorff (1972); Holtslag and Moeng (1991); Holtslag and Boville (1993). It should be carefully noted that, unless explicitly mentioned, we do not use the term non-local for non-local transport in this paper.)

In the current paper we will present a length scale formulation that may serve as an in-between; it uses local stability (the Richardson number) in a non-local framework. The application of the scheme is restricted to near-neutral conditions near the surface and convective conditions. For strongly stable (with $Ri > 0.2$) we rely on a separate length scale formulation (see Appendix B). We will illustrate the behavior in some idealized cases: a diurnal cycle of dry (convective) BL, a diurnal cycle of a Cumulus topped boundary layer, and a quasi-stationary case of a near-decoupled Stratocumulus cloud-topped boundary layer. In addition, we will show that the concept can be successfully applied to a regional atmospheric climate model (RACMO) and compare results to near surface measurements at the Cabauw tower (the Netherlands).