Lecture 5.1 Nonlocal Parameterizations for Unsaturated BLs

In this lecture, we describe three nonlocal parameterizations for unsaturated BLs:

1. Holtslag-Boville scheme (used in CCM3)
2. Blackadar scheme (MM5)
3. UW PBL scheme (used by Bob Brown's group for using satellite microwave scatterometer measurements of surface wind to determine geostrophic wind.)

We describe 1 and 2 in the notes; 3 will be discussed by guest-lecturer Dr. Ralph Foster.

Holtslag-Boville Scheme

References:

Troen,, I., and L. Mahrt, 1986: A simple model of the atmospheric boundary layer: Sensitivity to surface evaporation. *Bound.-Layer Meteor.*, **37**, 129-148.

Holtslag, A. A. M., and C.-H. Moeng, 1991: Eddy diffusivity and countergradient transport in the convective atmospheric boundary layer . *J. Atmos. Sci.*, **48**, 1690-1698.

Holtslag, A. A. M., and B. A. Boville, 1993: Local versus nonlocal boundary layer diffusion in a global climate model. *J. Climate*, **6**, 1825-1842.

Holtslag and Moeng (1991, *JAS*) examined the prognostic equation for an advected scalar *a* in a surface-heated convective BL. By modeling the individual terms, they concluded that

$$\overline{w'a'} = -K_a\left(\frac{\partial a}{\partial z} - \gamma_a\right) \quad 0 < z < h$$

The second term on the right, which can be interpreted as a nonlocal flux of *a*, is due to boundary-layer filling convective eddies which transport the surface flux of *a* upward regardless of the local gradient of *a*. Assuming the surface flux of *a* is positive, the result of the nonlocal term is to produce a BL with in which *a* decreases less with height than if pure first-order closure were used.

$$K_a = kw_t z(1 - z/h)^2, \quad k = 0.4 \text{ is von Karman constant}$$

Holtslag and Boville 1993

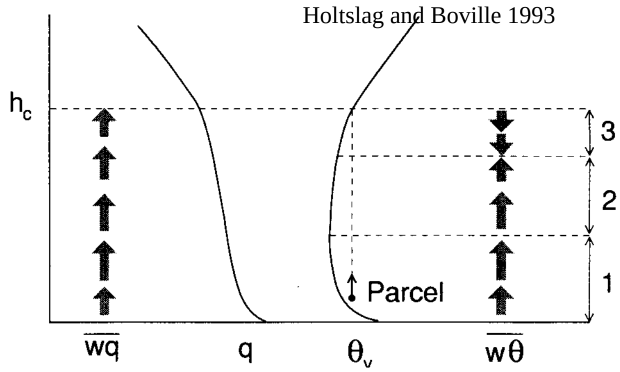

FIG. 2. Typical vertical profiles for (virtual) potential temperature Θ_v and specific humidity q for a dry convective boundary layer [modified after Stull (1991)]. The arrows to the left illustrate the specific humidity flux $\overline{wq}$, and the arrows to the right, the heat flux $\overline{w\theta}$. Also, an uprising parcel is indicated up to its intersection height h_c. The three regions are discussed in the text.

$$\gamma_a = A\frac{w_*(\overline{w'a'})_0}{w_t^2 h}, \quad A = 7.2$$

$$w_t = \Pr\{u_*^3 + c_1 w_*^3\}, \; c_1 = 0.6, \Pr = 1 \text{ (momenta), } 0.6 \text{ -1 (scalars)}$$

$$h = \frac{Ri_{cr}[u(h)^2 + v(h)^2]}{\frac{g}{\theta_s}(\theta_v(h) - \theta_s)}, \; \mathrm{Ri}_{cr} = 0.5 \text{ (optimal value depends on model } \Delta z)$$

The nonlocal flux is largest near the center of the boundary layer, with a maximum value

$$\overline{w'a'}_{\text{nonlocal, max}} = K_{a,\,\max}\gamma_a = 0.43(w_*/w_t)\overline{w'a'}_0 \text{ at } z = h/3$$

Since the nonlocal flux is proportional to w_*/w_t, it is only active in unstable boundary layers where the convective velocity w_* is significant. In stable or neutral BLs, the parameterization reduces to a K-profile eddy diffusivity.

The surface fluxes are computed using an approximation to Monin-Obuhkov theory. In a coarsely resolved model, the actual gradient of a as a function of z is not explicitly computed, so bulk aerodynamic formulas due to Louis (1979, *Bound.-Layer Meteor.*), which are based only on the difference between the surface value a_0 and its value a_0 at the lowest gridpoint at height z_1, are used. The transfer coefficient for a scalar a, given roughness length z_0, is of the standard form

$$C_a = C_N F(\mathrm{Ri}_0), \quad \text{where } C_N = k^2/\ln^2(z_1/z_0)^2 \text{ is standard neutral transfer coeff.}$$

$$\mathrm{Ri}_0 = z_1(b_1 - b_0)/|\mathbf{u}_1|^2, \quad \text{where } b_i = g(\theta_{vi} - \theta_R)/\theta_R \text{ is mean buoyancy at level } i.$$

$$F(\mathrm{Ri}_0) = \begin{cases} 1 - \dfrac{15\mathrm{Ri}_0}{75C_N(\mathrm{Ri}_0 z_1/z_0)^{1/2}}, & \text{unstable } (\mathrm{Ri}_0 < 0) \\ \dfrac{1}{1 + 10\mathrm{Ri}_0(1 + 8\mathrm{Ri}_0)}, & \text{stable } (\mathrm{Ri}_0 > 0) \end{cases}$$

Note that $F(\mathrm{Ri}_0)$ is always positive regardless of how large Ri_0 is. This is because even if Ri_0 is too large to support steady turbulence at height z_1, there will be turbulence and turbulent fluxes closer to the ground which should modify the lowest model layer.

The nonlocal closure tends to produce a warmer, deeper convective BL than first-order closure. This is often a step in the right direction, but can be misleading for cloud-topped boundary layers where the estimated BL depth can be too deep.

Holtslag and Boville 1993

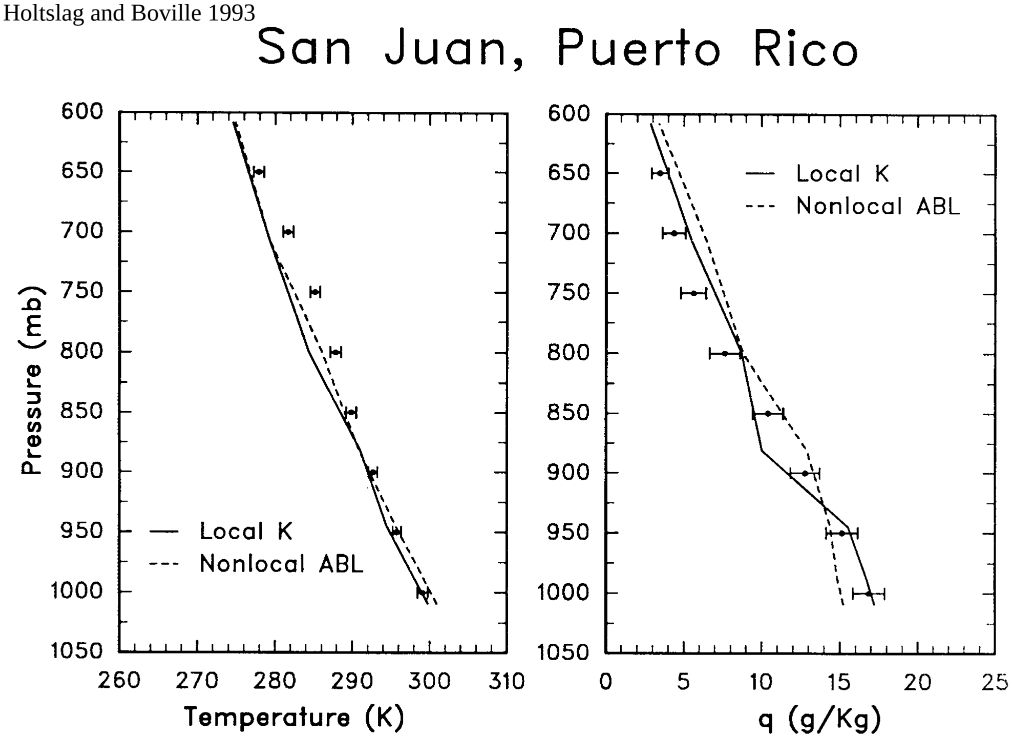

FIG. 3. As Fig. 1 but for San Juan, Puerto Rico (18.3°N, 66°W).

Comparison of CCM3 with local (solid) and nonlocal (dashed) closures with July climatology for San Juan, Puerto Rico (a trade-cumulus regime)

Blackadar convective BL (from Grell et al. 1994)

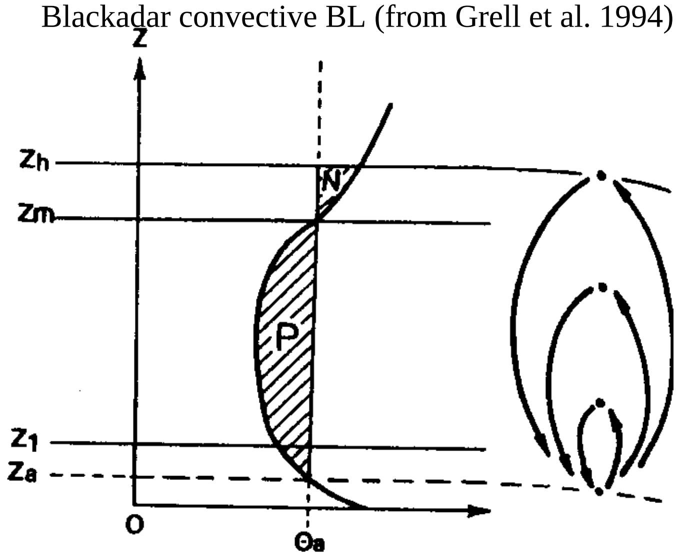

FIG. 2. Schematic diagram illustrating free convective module. Plumes originating at level z_a rise and mix at various levels, exchanging heat, moisture and momentum with air at these levels. Some thermals overshoot the level z_m of zero buoyancy. The ratio of negative area N on the thermodynamic diagram to the positive area P is the entrainment rate (see text).

Blackadar high-resolution PBL scheme

References

Blackadar, A. K., 1979:*Advances in Environmental Science and Engineering*, **1**, No. 1, Pfafflin and Ziegler, Eds., Gordon and Breach Publishers, 50-85.

Zhang, D.-L., and R. A. Anthes, 1982: A high-resolution motdel of the planetary boundary layer- sensitivity tests and comparisons with SESAME-79 data. *J. Appl. Meteor,* **21**, 1594-1609.

Grell, G. A., J. Dudhia, and D. R. Stauffer, 1994: *A Description of the Fifth-Generation Penn State/NCAR Mesoscale Model (MM5)*. NCAR Tech. Note NCAR/TN-398, pp. 91-97.

Like the Holtslag-Boville scheme, the Blackadar scheme distinguishes between stable and unstable BLs. For stable BLs, conventional first-order closure is used. Turbulence is reduced to weak 'background' values if $Ri_0 > 0.2$. Numerically efficient approximations to the M-O relations are used in the stable to neutral regime in which $h/L > -1.5$, where h is a diagnosed BL height.

For unstable BLs, a nonlocal scheme is used. It is based on conceptual models and observations of BL convection. The lowest model thermodynamic level is assumed to represent the surface layer and is labeled by subscript a. Vertical exchange is visualized as the result of plumes originating in the surface layer mixing with air at each level below h. The BL depth h is taken to be the maximum penetration height of undilute plumes. They are assumed to accelerate due to their buoyancy until they reach their level of neutral buoyancy z_{nb}. At this point their upward kinetic energy $w_p^2/2 \propto P$, where P is their vertically integrated buoyancy perturbation. Due to their inertia, the plumes overshoot, topping out at a level h at which their vertically integrated buoyancy deficit $N = -0.2P$ (see figure above). This defines the BL top:

$$\frac{N}{P} = \frac{-\int_{z_{nb}}^{h} b_p(z)dz}{\int_0^{z_{nb}} b_p(z)dz} = 0.2 \quad \text{at } z = h, \quad \text{where } b_p(z) = g(\theta_{va} - \theta_v(z))/\theta_R$$

The (unstable) stratification of the lowest model layer above the surface layer is assumed to be related to the sensible heat flux through this layer, following observations of Priestley (1956):

$$\overline{w'\theta_v'}_1 = B(\theta_{va} - \theta_{v,3/2})^{3/2}$$

where B is a coefficient that depends only on the heights of the first two model levels. In the surface layer,

$$\frac{\partial\theta_a}{\partial t} = -\frac{(\overline{w'\theta_v'}_1 - \overline{w'\theta_v'}_0)}{z_1}$$

These equations will reach an equilibrium in which θ_{va} is larger than $\theta_{v,3/2}$ by an amount sufficient to carry the surface heat flux out of the surface layer into the rest of the BL.

The scheme now postulates a mass exchange $\overline{m}$ between the surface layer and each other layer below $z = h$:

$$\bar{m} = \overline{w'b'}_1 / 0.64P\text{, where the buoyancy flux } \overline{w'b'}_1 = \frac{g}{\theta_R}\overline{w'\theta_v'}_1$$

The value of a scalar such as θ in the BL is now assumed to change due to turbulent exchange with the surface layer according to

$$\frac{\partial\theta}{\partial t} = \bar{m}(\theta_a - \theta)$$

For momenta, $\bar{m}$ is multiplied by a factor 1 - *z/h* to account for the fact the momentum mixing is somewhat less efficient than mixing of scalars in a convective BL.

Comparisons of this parameterization with LES results have not been presented, and two case studies presented by Zhang and Anthes (1982) show fair, but not excellent agreement with observed BL evolution over land. Thus, the convective, nonlocal part of this scheme should probably be regarded as being on a shakier footing than the Holtslag-Boville scheme. It is not entirely clear that either of these schemes is superior to first order closure in practice.