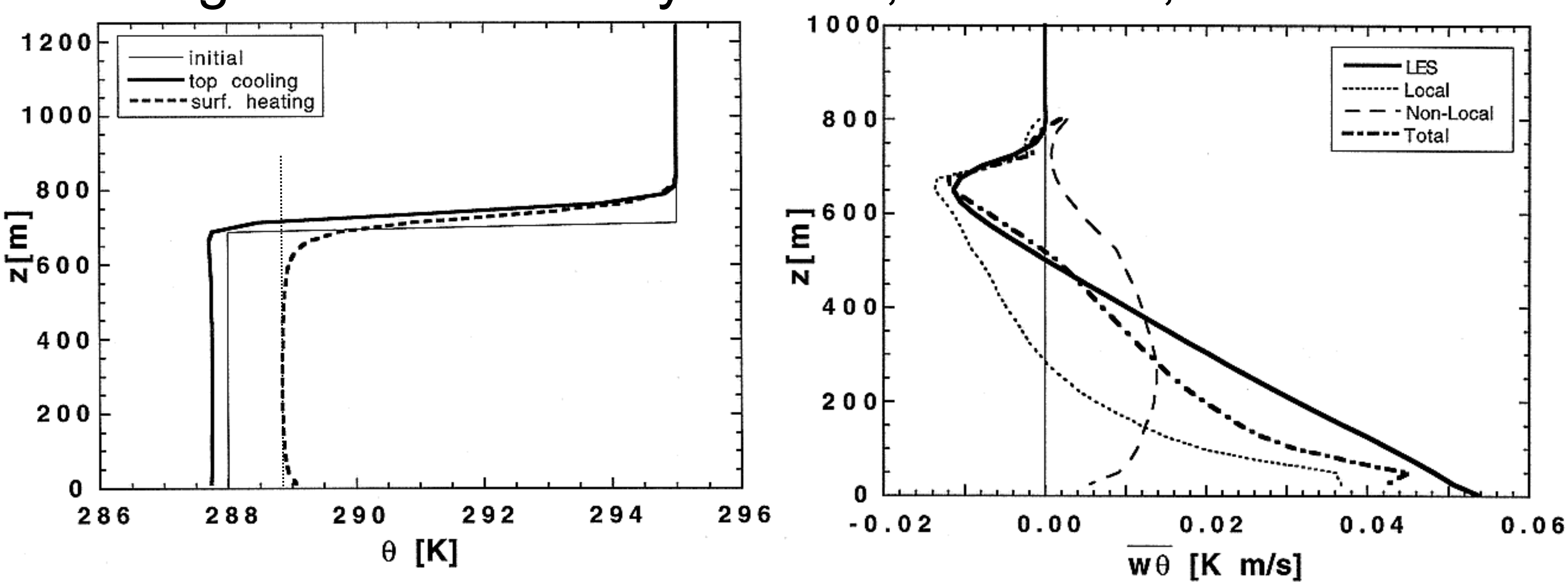
A challenge to downgradient diffusion: Countergradient heat transport

- In dry convective boundary layer, deep eddies transport heat
- This breaks correlation between local gradient and heat flux
- LES shows slight q min at z=0.4h, but w' q' >0 at z<0.8h
- 'Countergradient' heat flux for 0.4 < z/h < 0.8…first recognized in 1960s by Telford, Deardorff, etc.



Cuijpers and Holtslag 1998

Nonlocal K-profile schemes

$$\overline{w'a'} = -K_a(z)\frac{\partial a}{\partial z} + \text{another 'nonlocal' term}$$

(Holtslag-Boville in CAM3/4, YSU in WRF, EDMF in ECMWF):

Derivation of nonlocal schemes

Heat flux budget: $$\frac{\partial}{\partial t}\overline{w'\theta'} = -\overline{w'w'}\frac{\partial\bar{\theta}}{\partial z} - \frac{\partial\overline{w'w'\theta'}}{\partial z} + \frac{g}{\theta_0}\overline{\theta'\theta'} - \frac{1}{\rho_0}\overline{\theta'\frac{dp'}{dz}}$$

S M T B P

Neglect storage S
Empirically:

$$T \approx B + 2\frac{w_*^2\theta_*}{h}$$

$$P = -aB - \frac{\overline{w'\theta'}}{\tau}$$

For convection, a=0.5, so

$$\overline{w'\theta'} = -\underbrace{\frac{\tau}{2}\overline{w'w'}}_{K_H(z)}\frac{\partial\bar{\theta}}{\partial z} + \tau\frac{w_*^2\theta_*}{h}$$

Take $\tau = 0.5h/w_*$ to get zero θ gradient at $0.4h$.

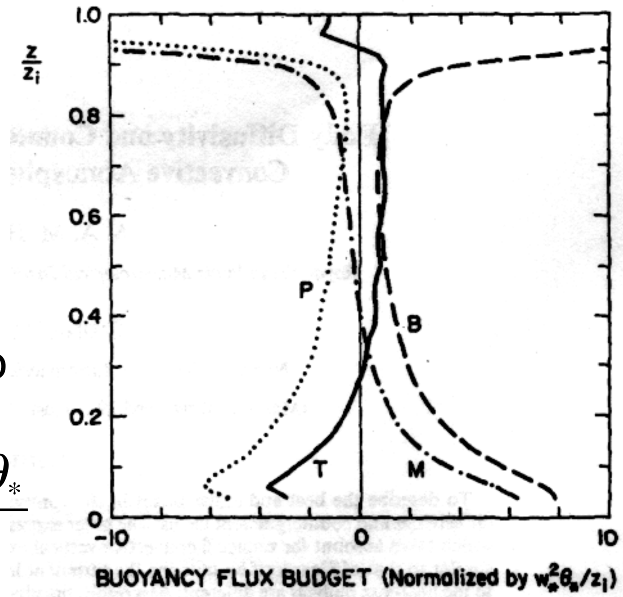


FIG. 1. The normalized terms at the rhs of the heat-flux equation (1), as a function of relative height (adopted from Moeng and Wyngaard 1989). The terms are defined in the text of section 2a.

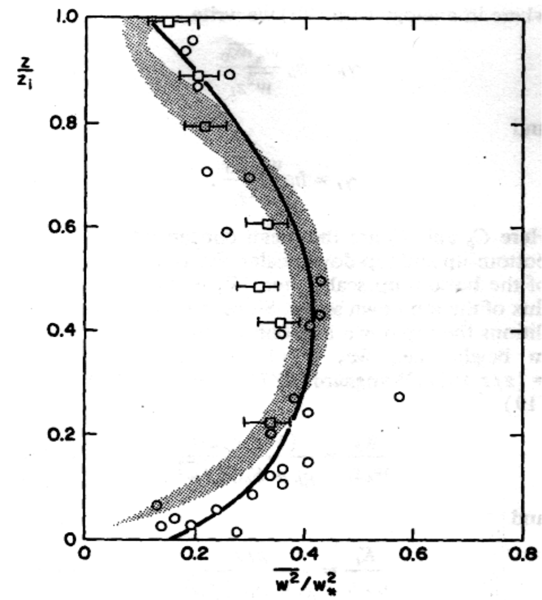


FIG. 4. The nondimensional vertical-velocity variance of (15a) (solid curve) in comparison with the $(96)^3$ LES data (shaded area; Moeng and Wyngaard 1989), the AMTEX data (circles; Lenschow et al. 1980), and convection tank experiments (squares; Deardorff and Willis 1985).

Holtslag and Moeng (1991)

Nonlocal parameterization, continued

This has the form $\overline{w'\theta'} = -K_H(z)\left(\frac{\partial\theta}{\partial z} - \gamma_\theta\right)$ where $\gamma_\theta = \frac{2w_*^2\theta_*}{\overline{w'w'}h}$

Although the derivation suggests γ_θ is a strong function of z, the parameterization treats it as a constant evaluated at z = 0.4h to obtain the correct heat flux there with $d\theta/dz = 0$:

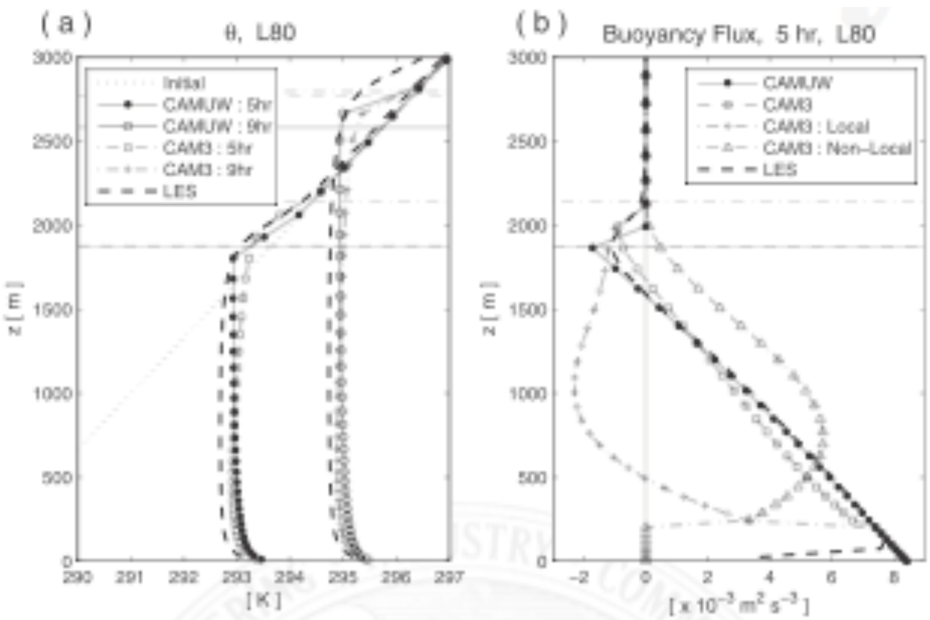
$$\overline{w'w'}(0.4h) = 0.4w_*^2 \quad \Rightarrow \quad \gamma_\theta = 5\theta_*/h.$$

The eddy diffusivity can be parameterized from vert. vel. var.:

$$\overline{w'w'}(z) = 2.8w_*^2 Z(1-Z)^2, \quad Z = z/h \quad \Rightarrow \quad K_H(z) = 0.7w_* z(1-Z)^2$$

With cleverly chosen velocity scales, this can be seamlessly combined with a K-profile for stable BLs to give a generally applicable parameterization (Holtslag and Boville 1993).

CBL comparison



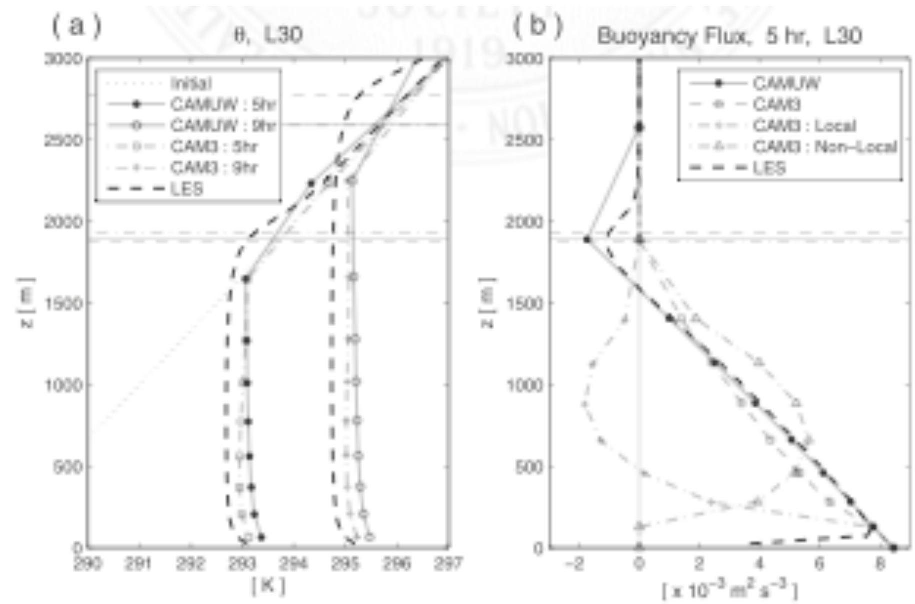


FIG. 6. As in Fig. 5, except with 30 vertical levels and a 1200-s time step.

Bretherton and Park 2009

- Sfc heating of 300 W m^{-2}
- No moisture or mean wind

- UW TKE scheme with entrainment closure and HB scheme give similar results at both high and low res.
- Overall, can get comparably good results from TKE and profile-based schemes on these archetypical cases.

EDMF

$$\overline{w'\phi'} \cong -K\frac{\partial\bar{\phi}}{\partial z} \qquad \overline{w'\phi'} \cong M(\phi_u - \bar{\phi})$$