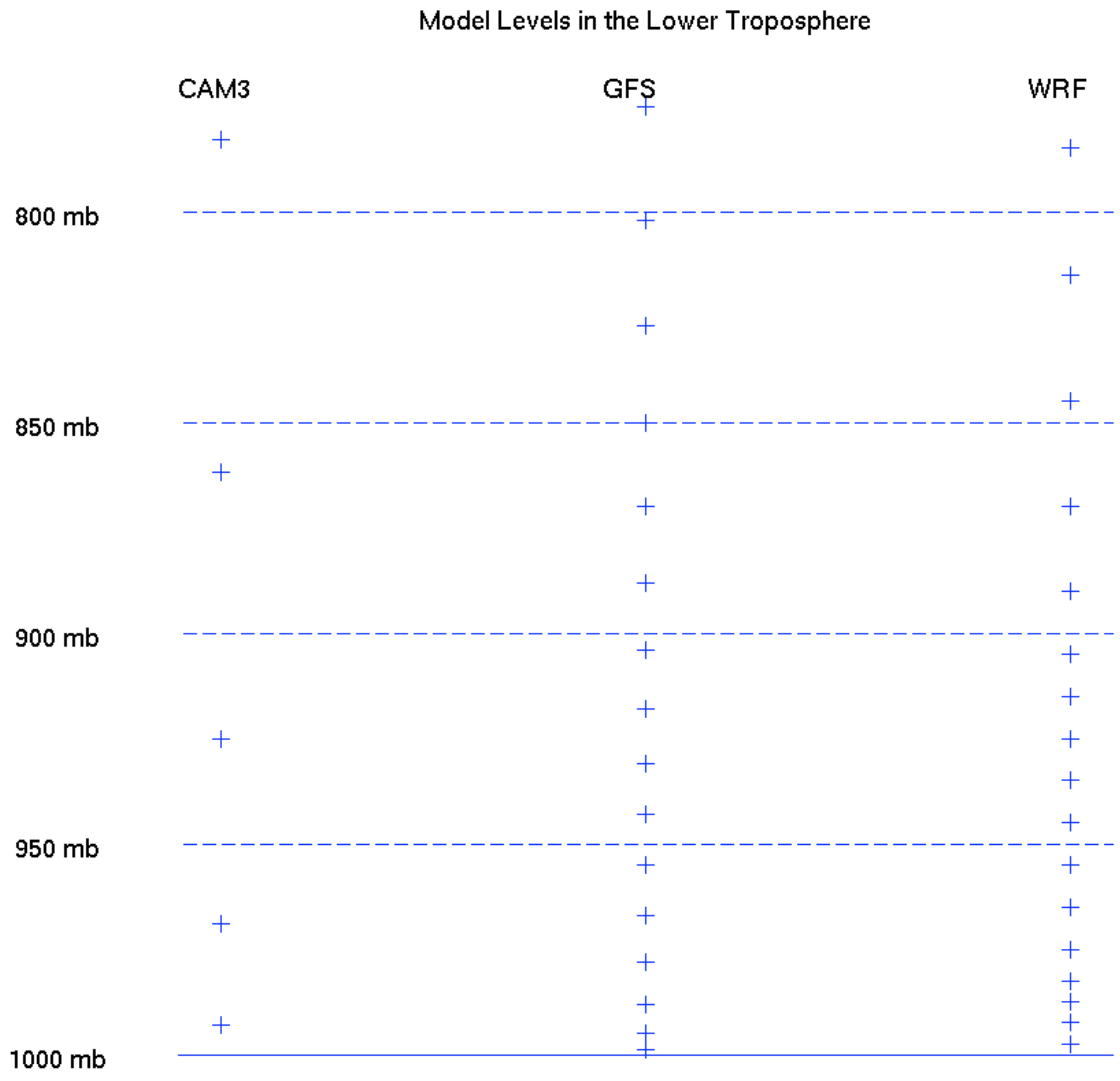
Vertical resolution of numerical models



Observational support for CBL entrainment flux closure

$$\overline{w'b'}(h) = -0.2B_0$$

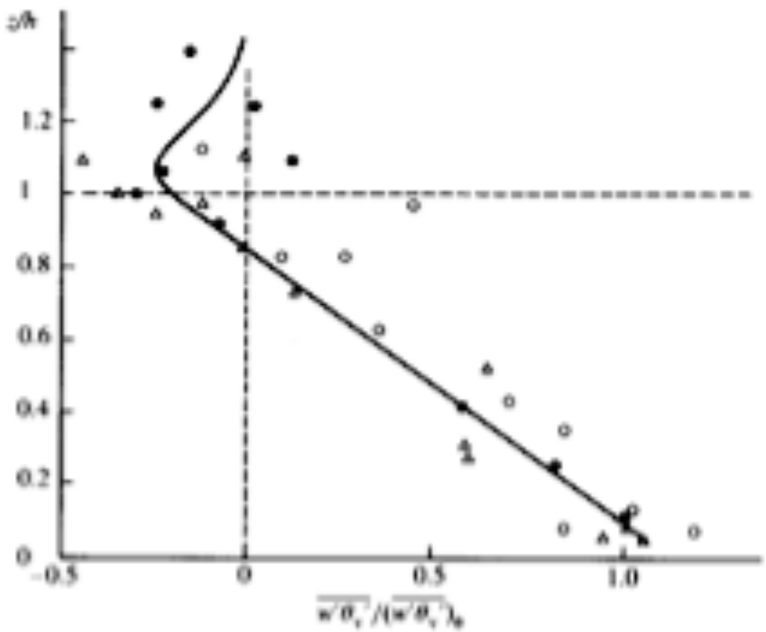
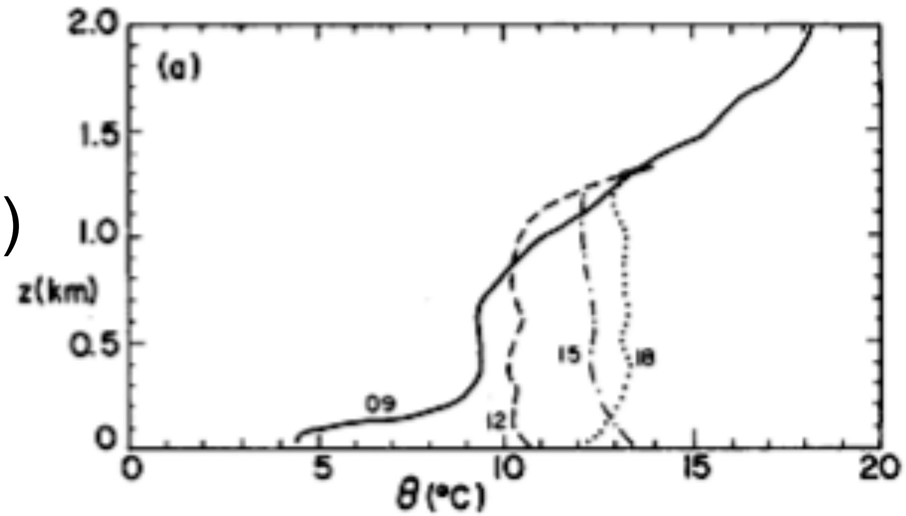


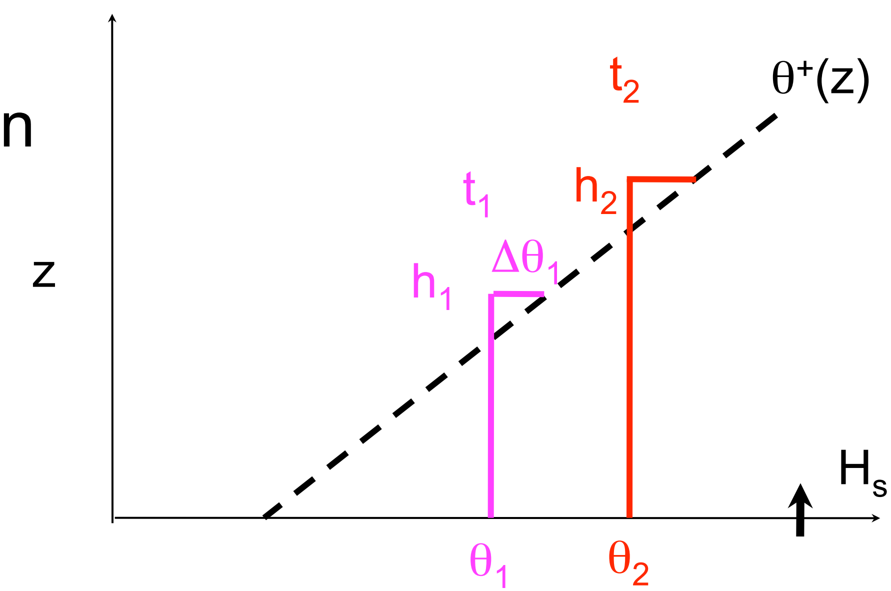
Fig. 6.2 Experimental data on the vertical variation of the virtual heat flux, normalized by its surface value; h is the depth of the mixed layer. Data are for three days from the 1983 ABL experiment; see Stull (1988, Figs. 3.1, 3.2 and 3.3). See also Fig. 6.23 of this volume.

Mixed-layer model of dry convective BL

Real
(Wangara)



MLM
idealization



Profile vs. forcing-driven turbulence parameterization

Mellor-Yamada turbulence closure schemes are **profile-driven**:

Nonturbulent processes destabilize u,v,θ profiles.

→ The unstable profiles develop turbulence.

- Such schemes (except 1st order closure) can be numerically delicate:

  Small profile changes (e.g. from slightly stable to unstable strat) can greatly change $K_{H,M}(z)$, turbulent fluxes, hence turbulent tendencies. This can lead to numerical instability if the model timestep Δt is large.

- TKE schemes are popular in regional models (Δt ~ 1-5 min).
- Most models use first-order closure for free-trop turbulent layers.

Alternate K-profile approach (next) is **forcing-driven**:

$K_{H,M}(z)$ are directly based on surface fluxes or heating rates.

- More numerically stable for long Δt
- Hence K-profile schemes popular in global models (Δt ~ 20-60 min).
- However, K-profile schemes only consider some forcings (e. g. surface fluxes) and not others (differential advection, internal radiative or latent heating), so can be physically incomplete.

K-profile method

- Parameterize turbulent mixing in terms of surface fluxes (and possibly other forcings) using a specified profile scaled to a diagnosed boundary layer height h.
- Example: Brost and Wyngaard (1978) - for stable BLs

$$K_m(z) = \underbrace{\frac{k u_* z}{\phi_m(z/L)}}_{\text{M-O form}} (1 - Z)^{3/2} \qquad (Z = z/h)$$

- h empirically diagnosed using threshold bulk Ri, e. g.

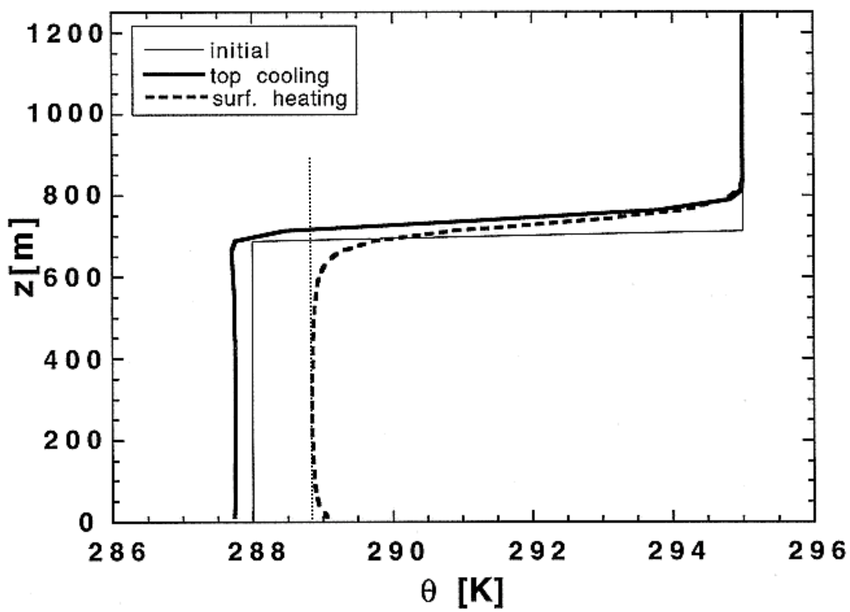
$$\frac{h\left(b(h) - b_{sfc}\right)}{\left(u(h) - u_{sfc}\right)^2 + \left(v(h) - v_{sfc}\right)^2 + 100 u_*^2} = \mathrm{Ri}_{crit} = 0.25$$

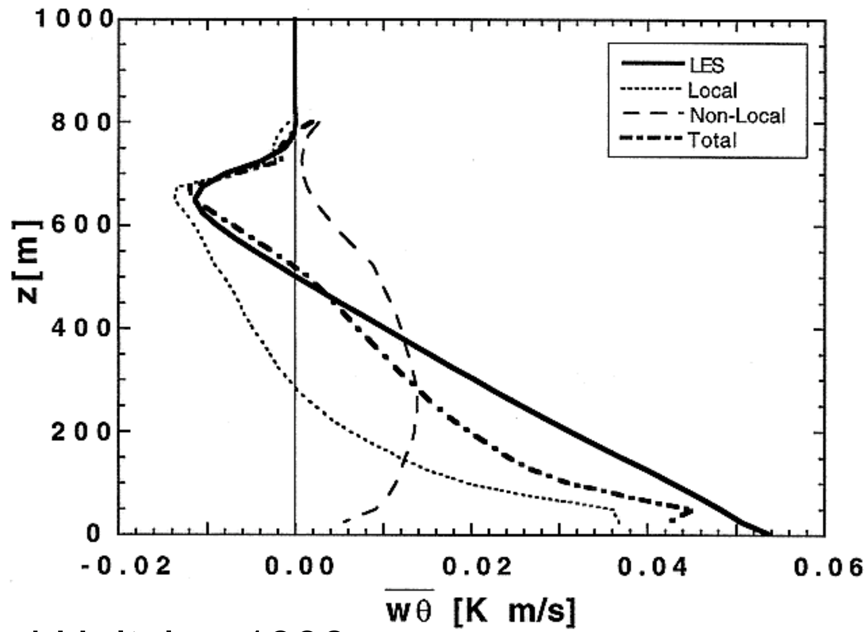
where 'sfc' = 20 m

Vogelezang&Holtslag 1996

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 θ min at z=0.4h, but $w'\theta'>0$ 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 schemes

This has spawned a class of **nonlocal** schemes for convective BLs (Holtslag-Boville in CAM3, MRF/ Yonsei in WRF) which parameterize:

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

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 $0.4h$.

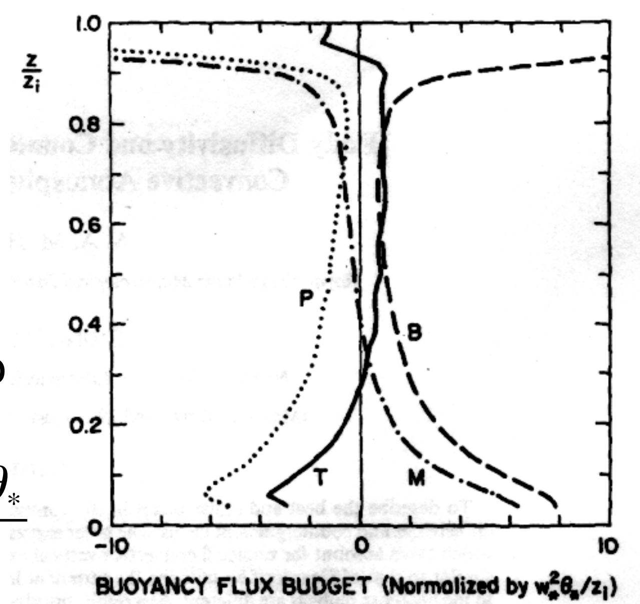


FIG. 1. The normalized terms at the rhs of the heat-flux equation (1), as a function of relative height (adopted from Moeng and Wyngaard 1989). The terms are defined in the text of section 2a.

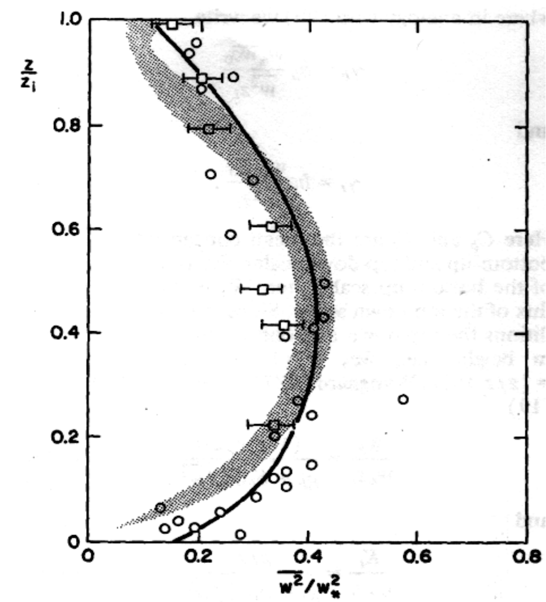


FIG. 4. The nondimensional vertical-velocity variance of (15a) (solid curve) in comparison with the $(96)^3$ LES data (shaded area; Moeng and Wyngaard 1989), the AMTEX data (circles; Lenschow et al. 1980), and convection tank experiments (squares; Deardorff and Willis 1985).

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).