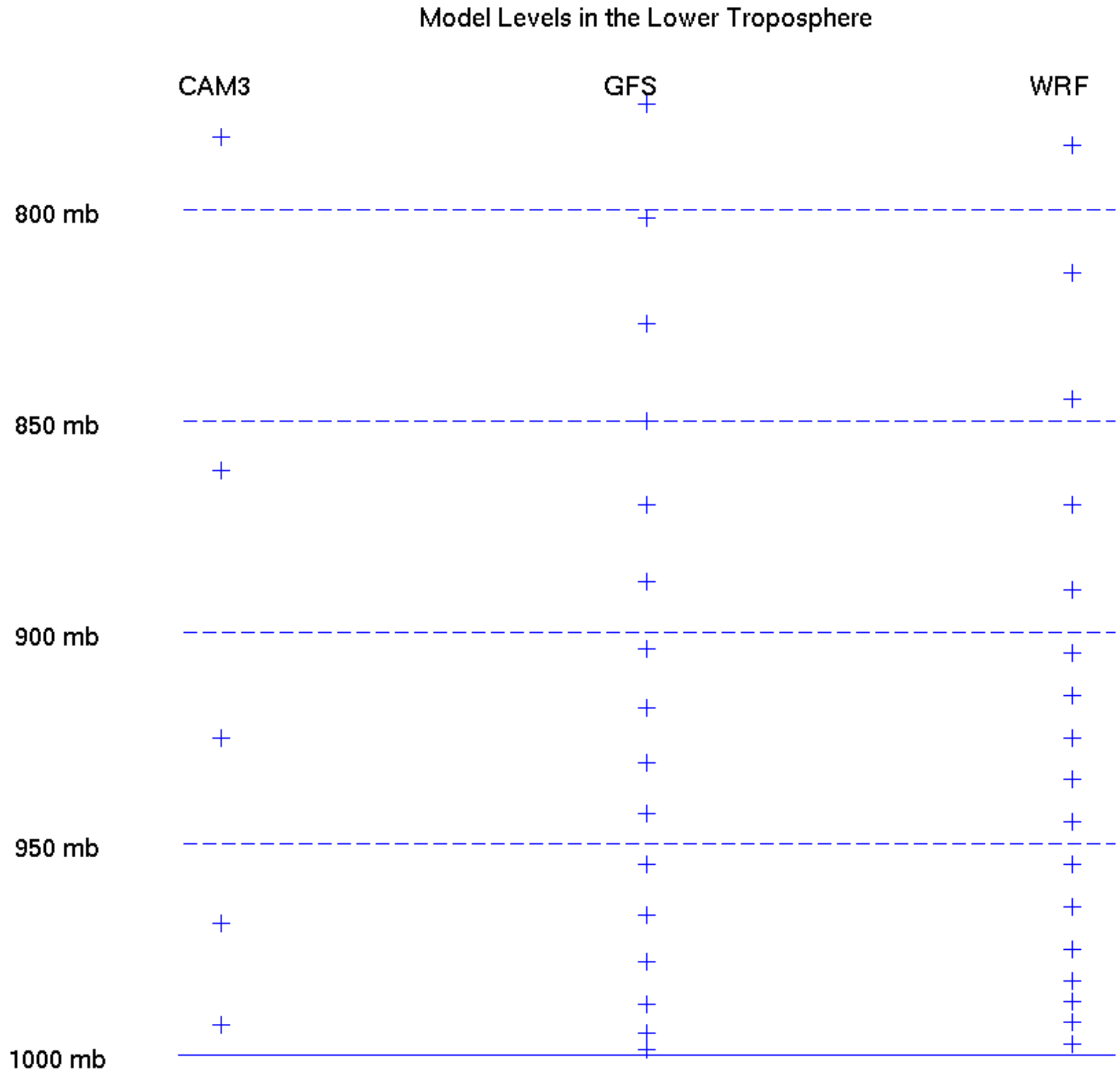
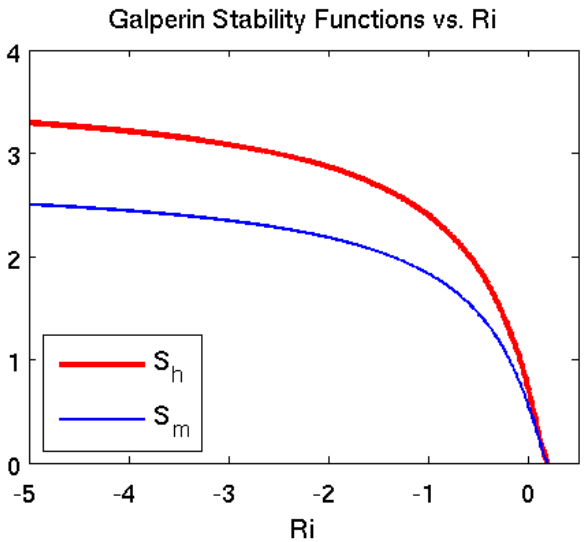
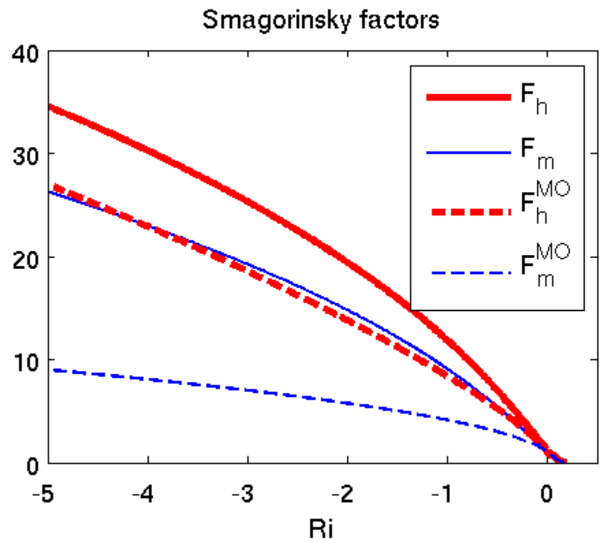
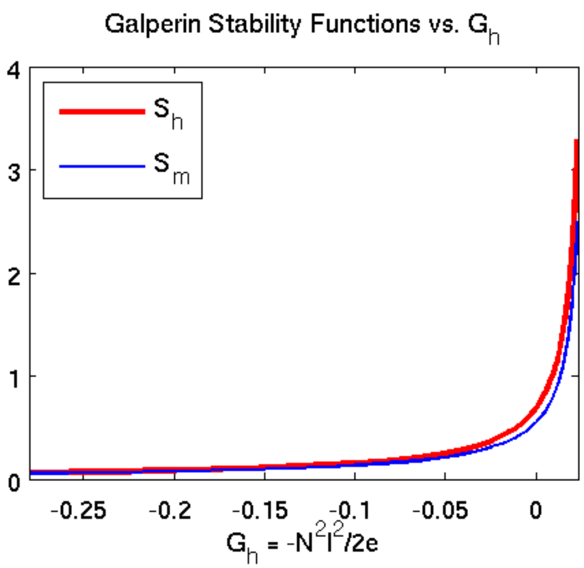
Vertical resolution of numerical models



M-O and Galperin stability factors







Profile vs. forcing-driven turbulence parameterization

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

Nonturbulent processes destabilize u, v, θ_v 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.

K-profile approach 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

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

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

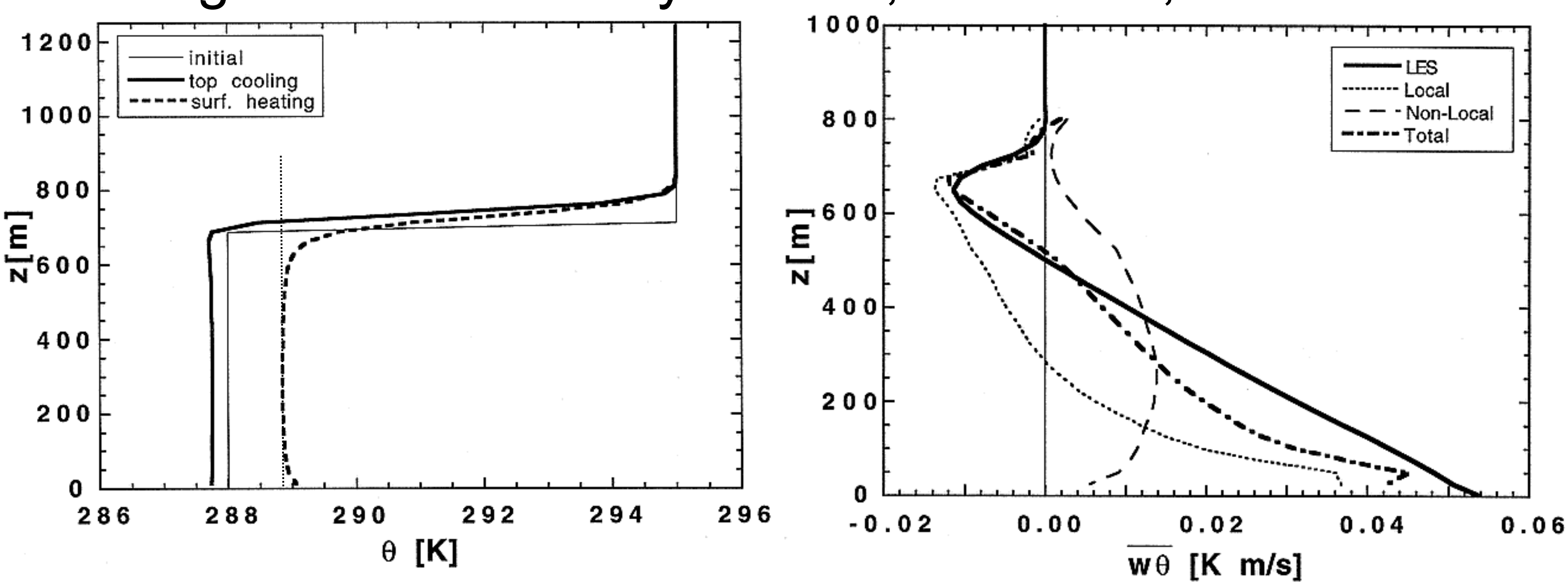
$$\frac{h\left(b(h) - b_{sfc}\right)}{\left(u(h) - u_{sfc}\right)^2 + \left(v(h) - v_{sfc}\right)^2 + 100u_*^2} = \mathrm{Ri}_{crit} = 0.25$$

where 'sfc' = 20 m

Vogelezang&Holtslag 1996

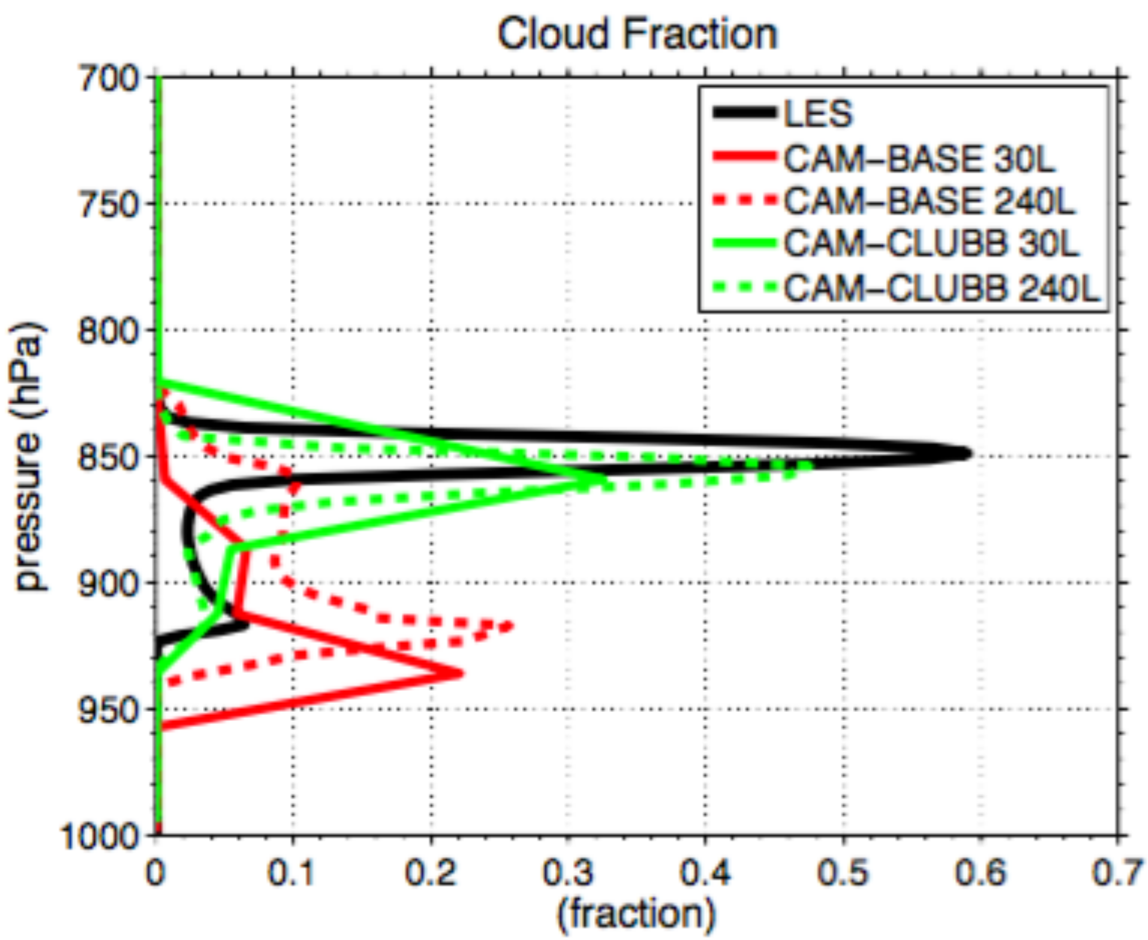
A challenge to downgradient diffusion: Countergradient heat transport

- In dry convective boundary layer, deep eddies transport heat
- This breaks correlation between local gradient and heat flux
- LES shows slight 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

CLUBB shines for marine Cu under Sc BLs



GCSS ATEX intercomparison case, Bogenschutz et al. 2012 GMD, Fig. 7a

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

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

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

Take ? = 0.5*h*/w_* to get zero ??gradient at 0.4*h.*

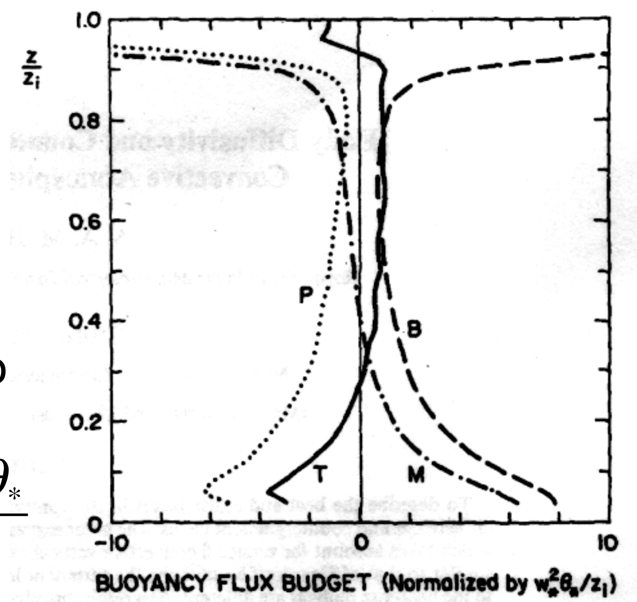


FIG. 1. The normalized terms at the rhs of the heat-flux equation (1), as a function of relative height (adopted from Moeng and Wyngaard 1989). The terms are defined in the text of section 2a.

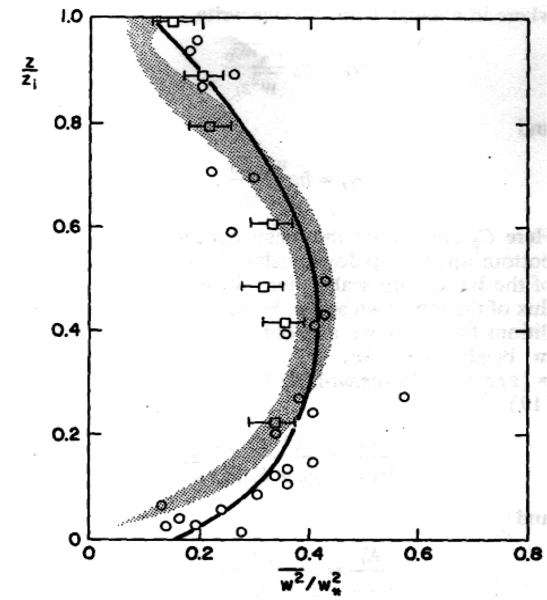


FIG. 4. The nondimensional vertical-velocity variance of (15a) (solid curve) in comparison with the $(96)^3$ LES data (shaded area; Moeng and Wyngaard 1989), the AMTEX data (circles; Lenschow et al. 1980), and convection tank experiments (squares; Deardorff and Willis 1985).

Holtslag and Moeng (1991)

Nonlocal parameterization, continued

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

Although the derivation suggests $?_{?}$ 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?/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.:

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

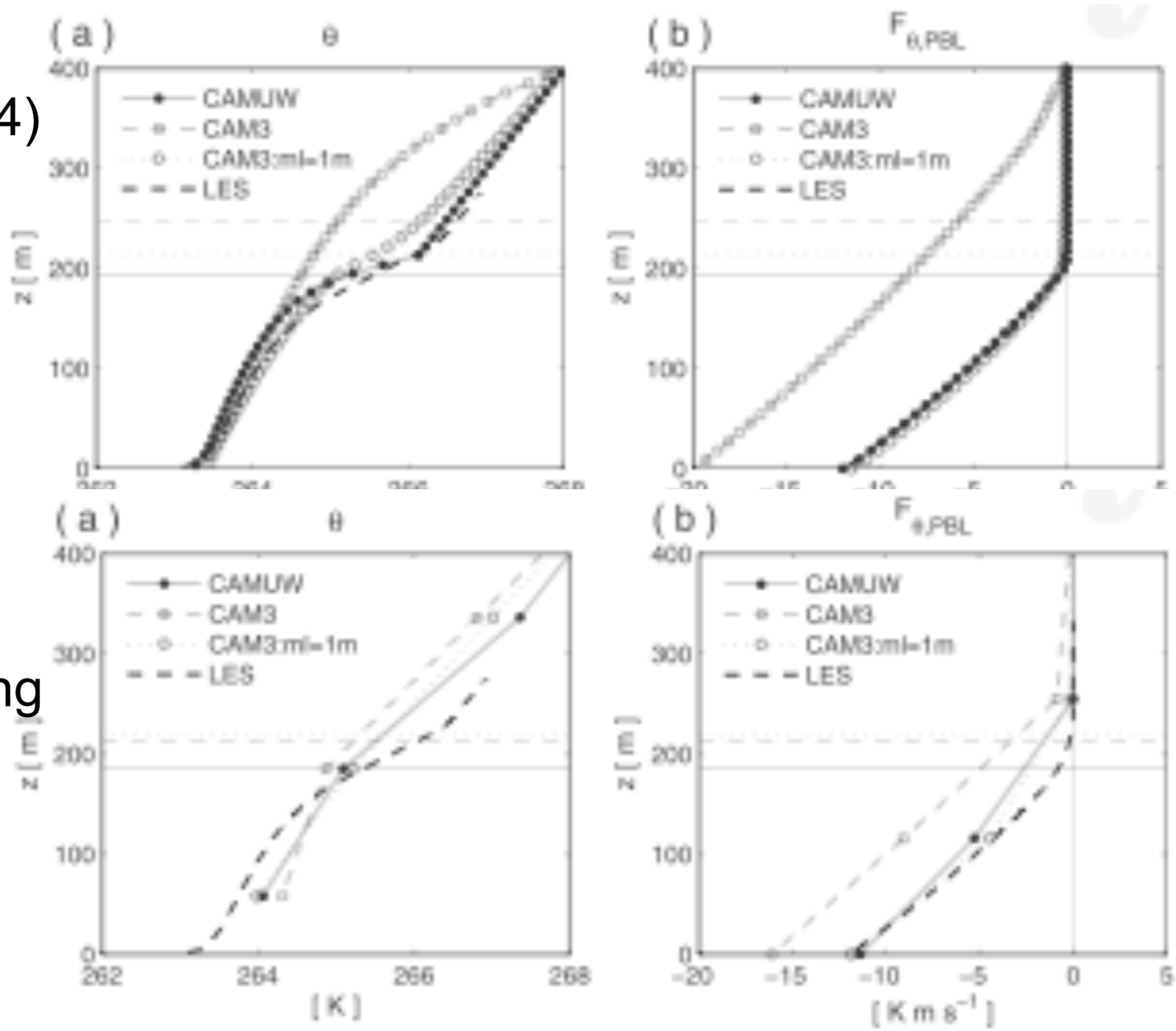
With cleverly chosen velocity scales, this can be seamlessly combined with a K-profile for stable BLs to give a generally applicable parameterization (Holtslag and Boville 1993).

Comparison of TKE and nonlocal K-profile scheme

UW TKE scheme (Bretherton&Park 2009) vs. Holtslag-Boville.

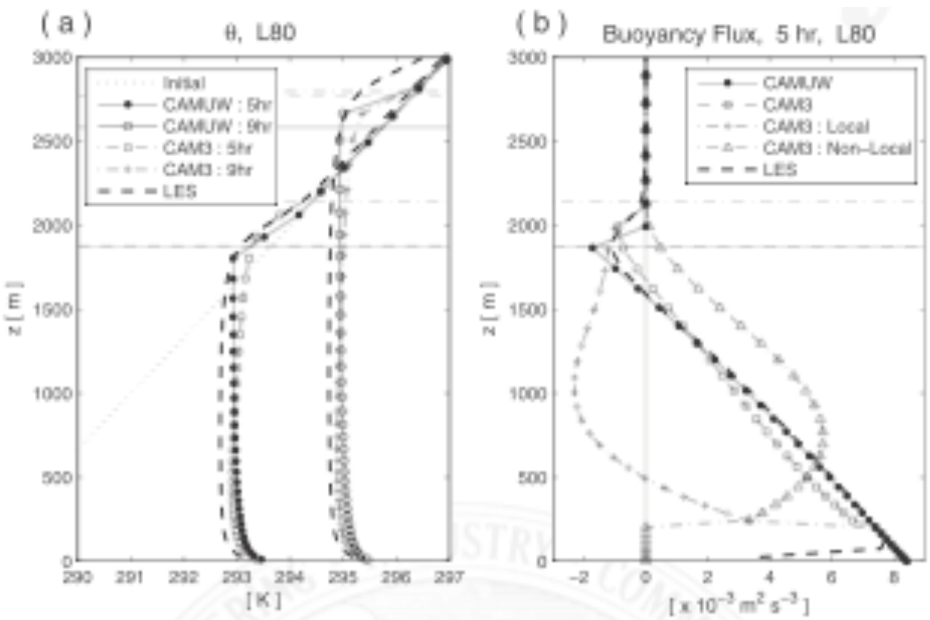
GABLS1 (Beare et al. 2004)
- Linear initial θ profile
- u_g = 10 m/s
- sfc cooled at 0.25K/hr
- 8-9 hr avg profiles

- UW and HB both do well
- Default CAM3 has too much free-trop diffusion, causing BL overdeepening



Bretherton and Park 2009

CBL comparison



Bretherton and Park 2009

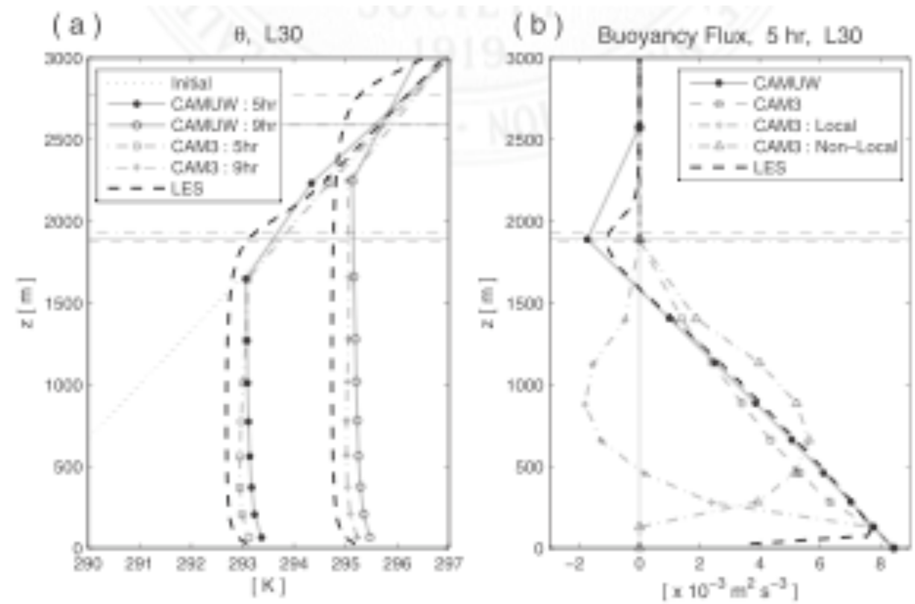


FIG. 6. As in Fig. 5, except with 30 vertical levels and a 1200-s time step.

- 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.