# An Eddy-Diffusivity Mass-Flux (EDMF) Boundary Layer Parameterization Combined with a Higher-Order Turbulence Closure Model in the NCEP GFS

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# Motivation

- NCEP GFS of which the vertical turbulent mixing scheme is based on first-order turbulence closure model suffers from a large cold near-surface temperature bias during sunset especially for clear, calm wind conditions.
- A higher-order turbulence closure model may better handle vertical turbulent mixing in the residual layer after sunset due to its memory of turbulence, and thus, may help reduce the near-surface temperature bias.
- Major problem of the higher-order closure model is under-development of daytime PBL growth due to lack of non-local mixing.
- The non-local mixing can now be included in the higher-order closure model by a mass-flux scheme which has been recently implemented into the GFS PBL scheme.
- For the higher-order turbulence closure model, we employ a turbulent kinetic energy (TKE) closure model.

# Development of a TKE-based EDMF PBL scheme

Current GFS hybrid EDMF PBL scheme

$$\overline{w'\phi'} = -(K_{sfc} + K_{Sc})\frac{\partial\overline{\phi}}{\partial z} + K_{sfc}\gamma_{\phi}$$ Weakly unstable PBL

$$\overline{w'\phi'} = -(K_{sfc} + K_{Sc})\frac{\partial\overline{\phi}}{\partial z} + M_u(\phi_u - \overline{\phi})|_{sfc}$$ Strongly unstable PBL

$$K_{sfc} = \Pr^{-1}\kappa w_s z\left(1 - \frac{z}{h}\right)^2 \qquad K_h^{Sc} = 0.85\kappa V_{Sc}\frac{(z - z_b)^2}{h_b - z_b}\left(1 - \frac{z - z_b}{h_b - z_b}\right)^{1/2}$$

TKE-based EDMF PBL scheme

$$\overline{w'\phi'} = -K_{\phi}\frac{\partial\overline{\phi}}{\partial z} + M_u(\phi_u - \overline{\phi})|_{sfc} - M_d(\phi_d - \overline{\phi})|_{Sc}$$

$$K_{\phi} = c l_k\sqrt{\overline{e}}, \qquad \overline{e} = 0.5\left(\overline{u'^2} + \overline{v'^2} + \overline{w'^2}\right)$$ Mean TKE

$l_k$ is a turbulent mixing length

# Development of a TKE-based EDMF PBL scheme

$$\frac{d\bar{e}}{dt} = -\frac{\partial}{\partial z}\left(\overline{w'e'} + \frac{1}{\rho}\overline{w'p'}\right) - \overline{u'w'}\frac{\partial \bar{u}}{\partial z} - \overline{v'w'}\frac{\partial \bar{v}}{\partial z} + \frac{g}{\bar{\theta}_v}\overline{w'\theta'_v} - D$$

Note that shear and buoyancy production terms of TKE are strongly influenced by the mass flux (MF) term.

$$\overline{w'\phi'} = -K_\phi \frac{\partial \bar{\phi}}{\partial z} + M_u(\phi_u - \bar{\phi})|_{sfc} - M_d(\phi_d - \bar{\phi})|_{Sc}$$

$$\overline{w'e'} + \frac{1}{\rho}\overline{w'p'} \approx \overline{w'e'} = -K_e \frac{\partial \bar{e}}{\partial z} + M_u(e_u - \bar{e})|_{sfc} - M_d(e_d - \bar{e})|_{Sc}$$

$$D = c_d \frac{\bar{e}^{3/2}}{l_d}$$

TKE dissipative rate

$c_d = 0.714$ (Bougeault & Lacarrere [BL], 1989)

$$c_p \frac{\partial \bar{T}}{\partial t} \approx D$$

TKE dissipative heating

# Development of a TKE-based EDMF PBL scheme

Turbulent mixing length scale ($l_k$): combination of formulation for surface layer ($l_1$) and a characteristic length scale ($l_2$)

$$\frac{1}{l_k} = \frac{1}{l_1} + \frac{1}{l_2}$$

$$l_1 = \kappa z / 3.7 \qquad z/L \geq 1$$

$$l_1 = \kappa z \left(1 + 2.7\frac{z}{L}\right)^{-1} \qquad 0 \leq z/L < 1$$

$$l_1 = \kappa z \left(1 - 100\frac{z}{L}\right)^{0.2} \qquad z/L < 0$$

Nakanishi (2001)

$$l_2 = \left(l_{up} l_{down}\right)^{1/2} \qquad l_d = l_2$$

$$\int_z^{z+l_{up}} \frac{g}{\overline{\theta}_v}\left(\overline{\theta}_v(z) - \overline{\theta}_v(z')\right)dz' = \overline{e}(z)$$

$$\int_{z-l_{down}}^{z} \frac{g}{\overline{\theta}_v}\left(\overline{\theta}_v(z') - \overline{\theta}_v(z)\right)dz' = \overline{e}(z)$$

BL (1989) relates the length scale to the distance that a parcel having an initial TKE can travel upward and downward before being stopped by buoyance effects.

In original BL (1989)

$l_2 = \min\left(l_{up}, l_{down}\right)$ for $l_k$ $\qquad$ $l_d = \left(l_{up} l_{down}\right)^{1/2}$

# Development of a TKE-based EDMF PBL scheme

1) MF scheme for updraft due to daytime surface heating

$$\frac{\partial w_u^2}{\partial z} = -b_1 \varepsilon w_u^2 + b_2 g \frac{\theta_{v,u} - \overline{\theta}_v}{\overline{\theta}_v}$$

Updraft velocity equation

$b_1$=2.0, $b_2$=4.0

$$M_u = a_1 w_u$$

$a_1$=*0.1* (core updraft fraction), Soares et al. (2004)

$$\frac{\partial \phi_u}{\partial z} = -\varepsilon(\phi_u - \overline{\phi}), \qquad \phi = \theta, q_v, ....$$

$$\theta_{v,u}(z_1) - \overline{\theta}_v(z_1) = \alpha \frac{(\overline{w'\theta_v'})_s}{e^{1/2}(z_1)}$$

$\alpha$=1.0

Entrainment rate: $\varepsilon = \dfrac{c_e}{l_2 + \Delta z}$

$c_e$=*0.7* & $\varepsilon$=min($\varepsilon$, 0.002)

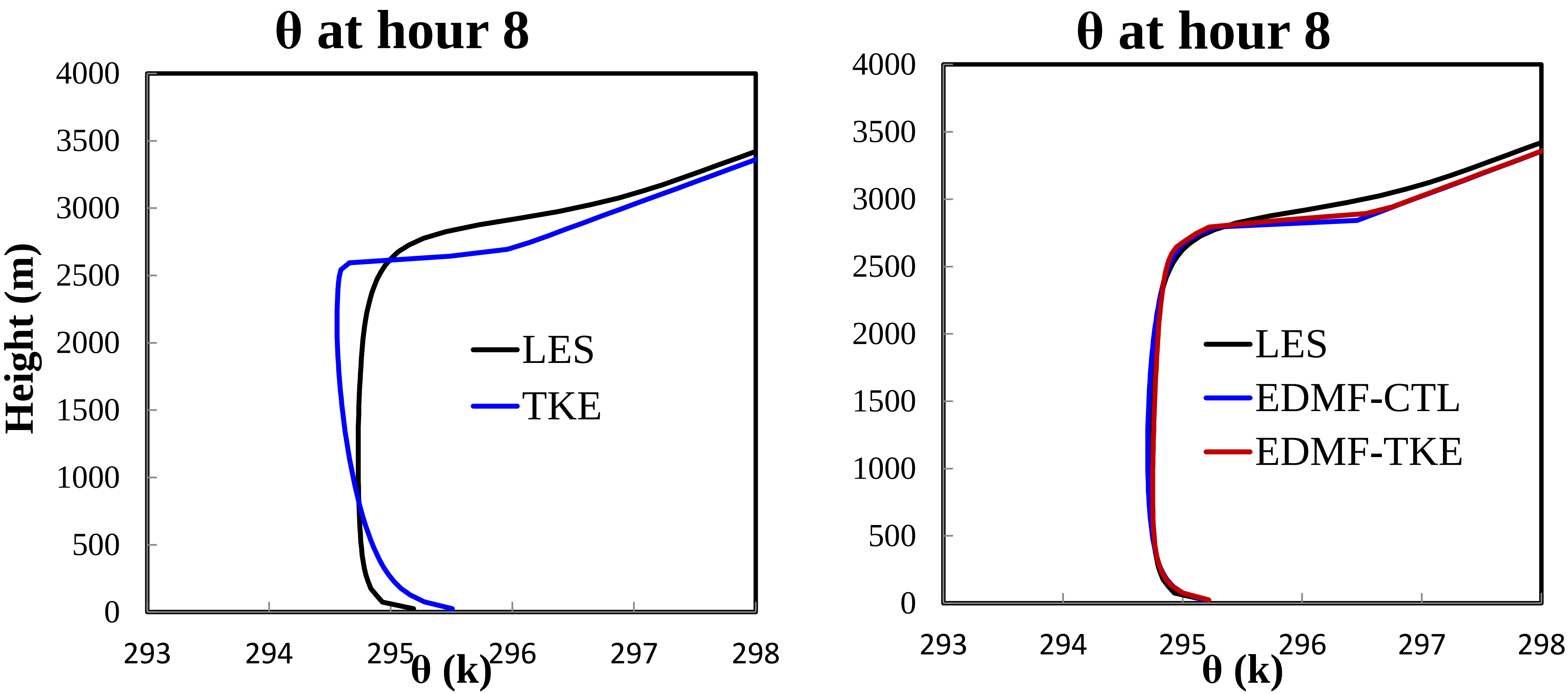
Witek et al. (2011): $\varepsilon = \dfrac{c_e}{l_2}$

2) $M_d$ and $\phi_d$ for stratocumulus-top-driven downdraft are also derived in a similar way to updraft above (not shown)

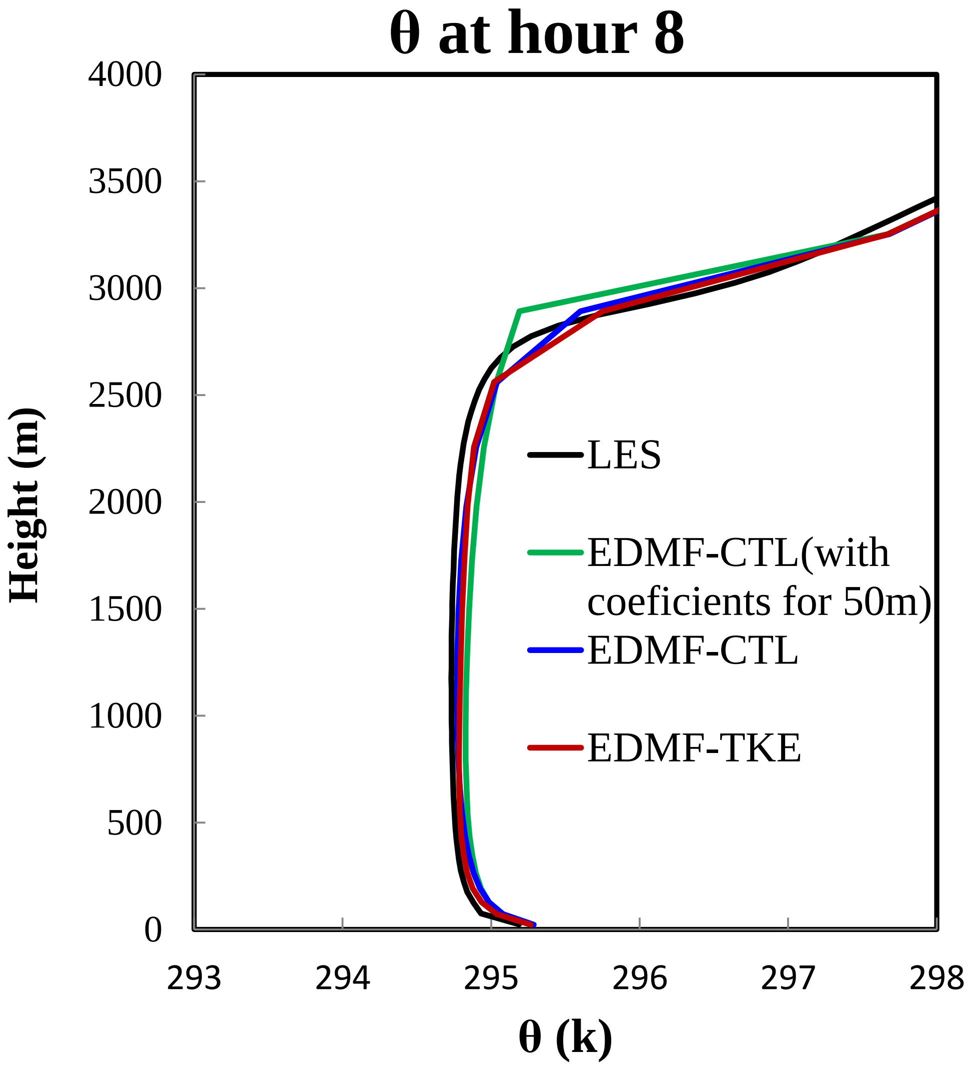
# GFS Single Column Model (SCM) experiments

- Initial $\theta$ profile: $\theta = 288\ K + (3\ K\ km^{-1})z$
- Constant buoyancy flux at surface: $8 \times 10^{-3} m^2 s^{-3}$
- Vertical resolution: $\Delta z = 50m$
- These settings are same as LES, the integrations have been conducted for 8 hours, and the SCM results are compared with the LES at 8 forecast hours.
- For the SCM, the integration was continued for additional 12 hours with a negative constant heat flux of -0.2 $Kms^{-1}$ after 8*h* PBL development.
- The experiments were also conducted with the coarse operational GFS vertical resolution which is about $\Delta z = 170m$ at $z = 1km$ and $\Delta z = 260m$ at $z = 2km$ with 64 vertical levels.

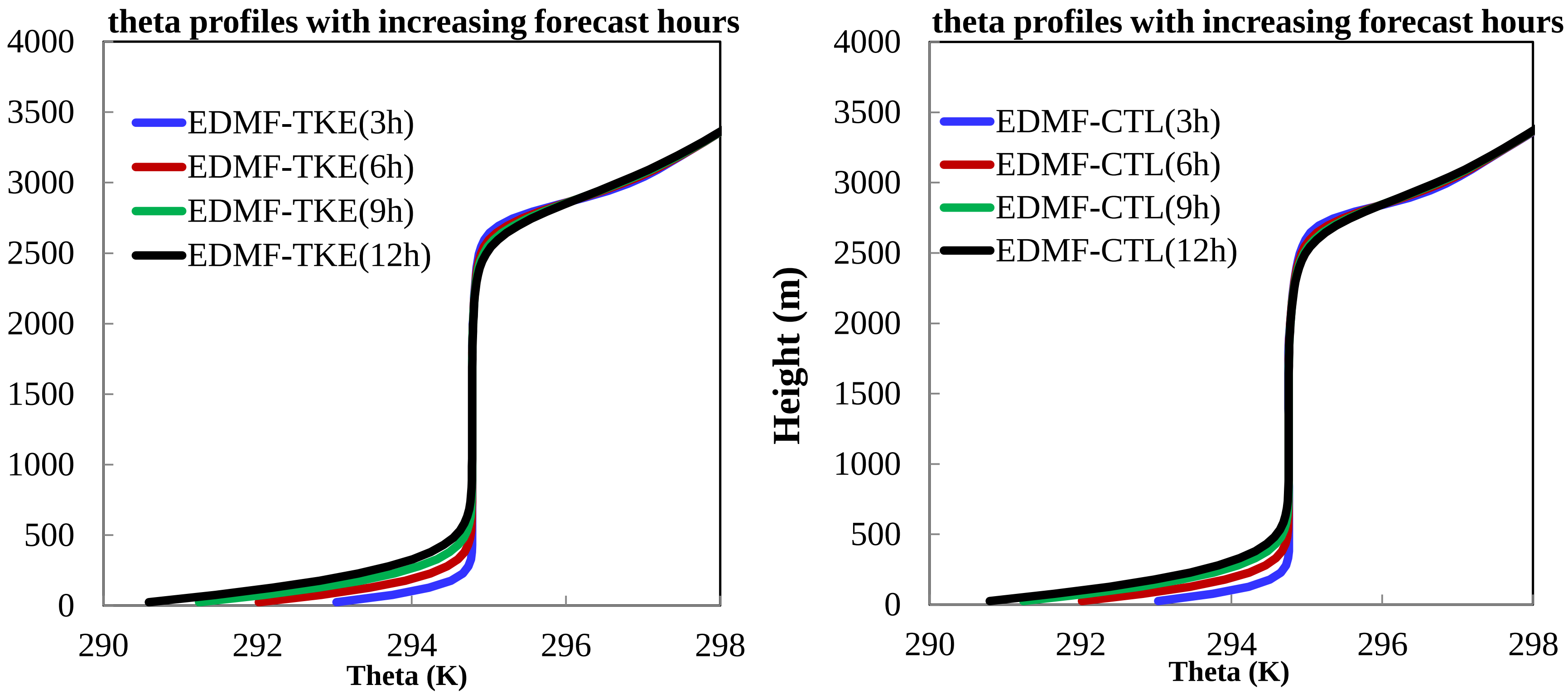
# SCM result of local TKE closure and TKE-based EDMF schemes compared with LES

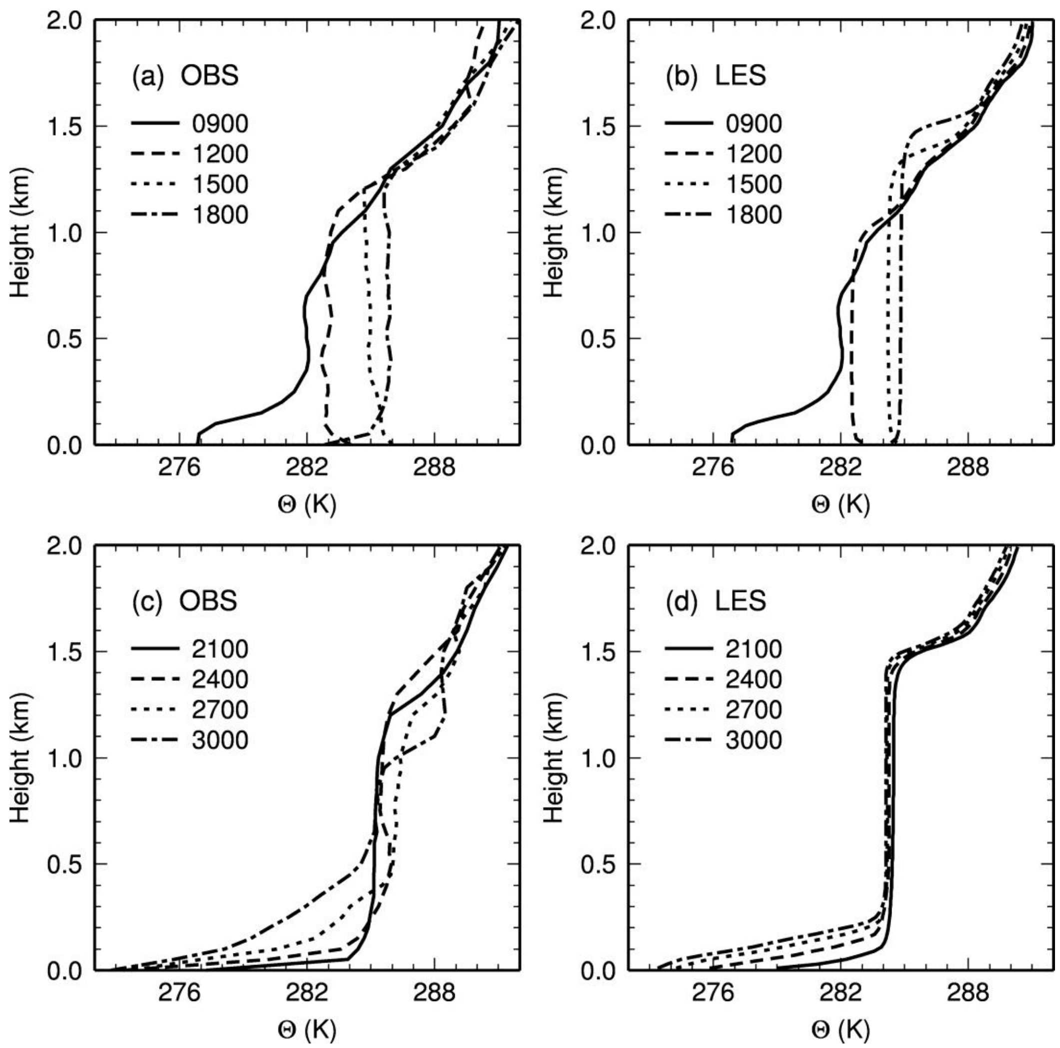


# SCM results with current operational GFS vertical grid size (L64)



# EDMF-TKE & EDMF-CTL SCM results for $\theta$ profiles with increasing forecast hours for a given constant surface cooling after sunset





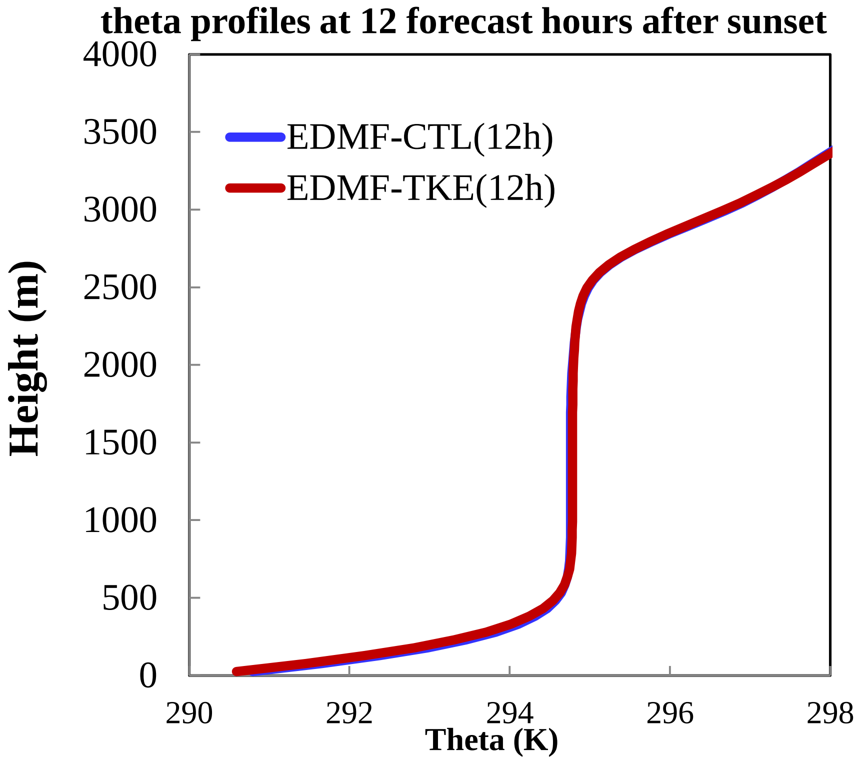

Lack of PBL after 1500 LST in observation is a result of subsidence in a high pressure system that is not included in LES.

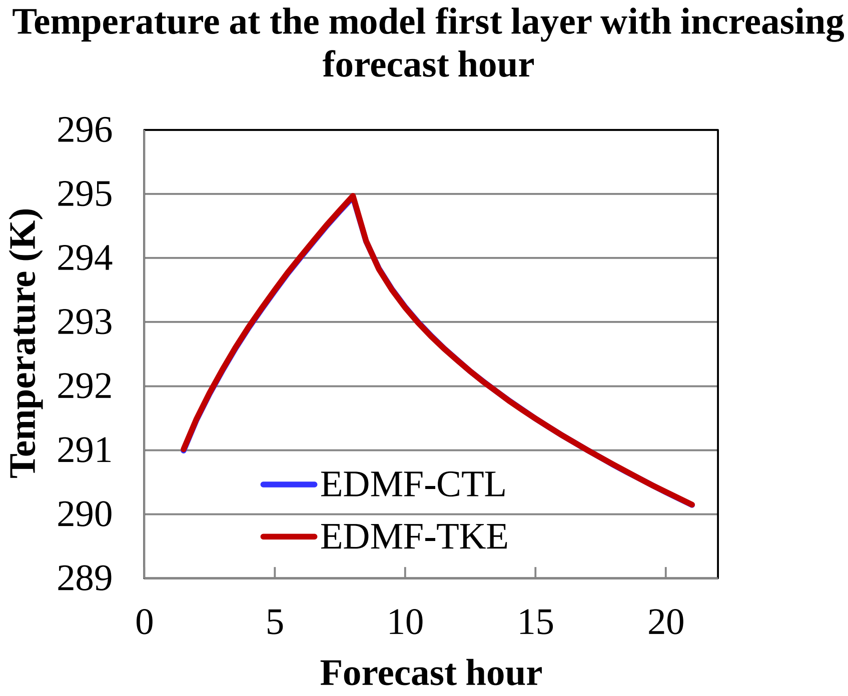
The discrepancy between LES and observation especially after 2400 LST could be a mesoscale horizontal advection that is not included in LES.

OBS: Wangara experiment (Clarke et al. 1971)

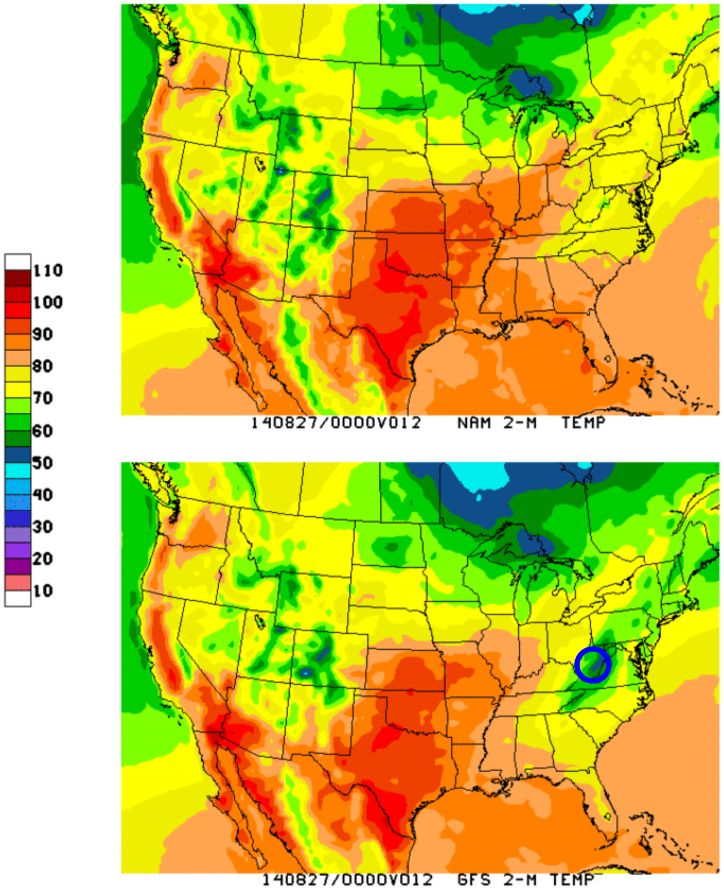
After Nakanishi et al. (2014)

# Comparison of $\theta$ profile & model first layer temperature

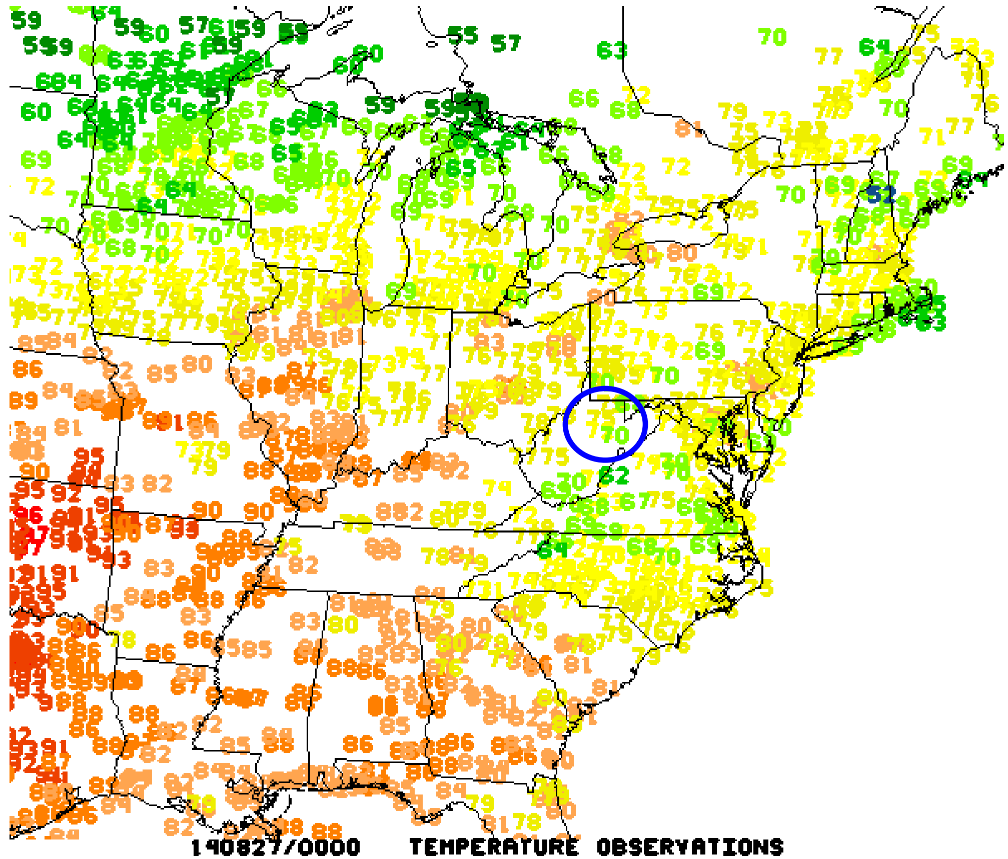


# Cold 2-m temperature bias in GFS over Appalachian mountains during sunset (00Z)




GFS at 00Z (12 FH)

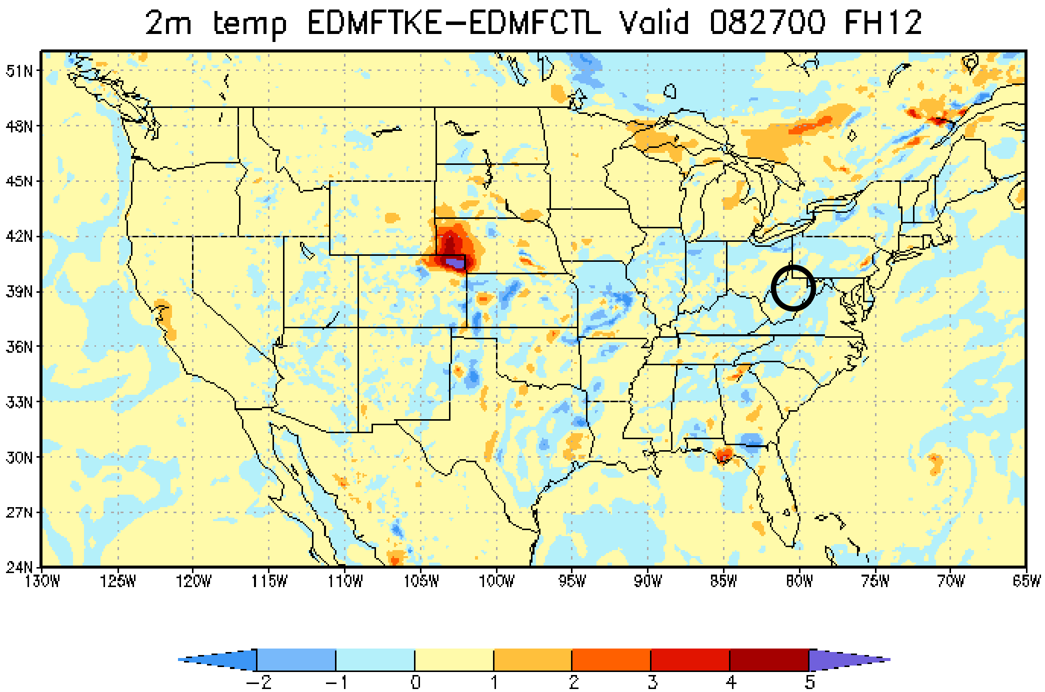


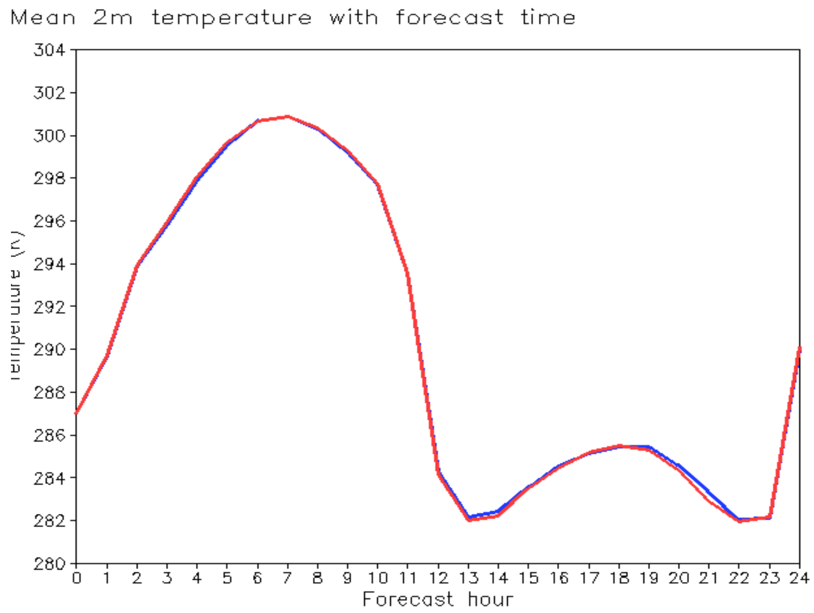

Obs at 00Z, 08/27/2014

Courtesy: Geoff Manikin (NCEP/EMC)

# Comparison of 2-m temperature (K) for 3D real case run

[blue: EDMF-CTL, red: EDMF-TKE]




EDMFTKE – EDMFCTL
at 00Z, 08/27/2014 (12 FH)

# Summary and conclusion

- A TKE-based EDMF PBL scheme has been developed and successfully simulates daytime well-mixed PBL, nighttime deepening stable boundary layer (SBL) and residual layer above the SBL, with a good agreement with the LES results.
- The new scheme predicts a PBL feature very similar to that from the current operational GFS hybrid EDMF PBL scheme (which is based on first-order K-profile method) although a significant difference is found in some areas in a 3D real case run, and thus, it doesn't help to reduce the cold 2-m temperature bias during sunset (which would be more related to the surface layer physics).
- Unlike the present GFS EDMF scheme, however, the tunable parameters in the new scheme is not much sensitive to vertical grid resolution.
- For future studies, we plan to test the new scheme for
    1) marine stratocumulus-topped boundary layer case (e.g., DYCOMS experiment)
    2) stable boundary layer case (e.g., GABLES experiment)
    3) real time forecasts for longer term in the current operational GFS

Thank you!!