# Vertical Turbulent Mixing Scheme in FV3GFS

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# Introduction

$$\frac{\partial \bar{\phi}}{\partial t} = -\frac{\partial \overline{w'\phi'}}{\partial z} + F_{\phi}$$

(1) (2)

*Φ*: *θ*, *q*, *u*, *v*, ….

(1)Tendency due to subgrid cumulus convection, turbulent mixing, and gravity wave drag.

(2) All tendency terms due to advection and diabatic processes.

# EDMF PBL scheme

EDCG--Eddy-Diffusivity Counter-Gradient scheme

$$\overline{w'\phi'} = -K\left(\frac{\partial\overline{\phi}}{\partial z} - \gamma\right) \qquad \gamma = 6.5\frac{\overline{(w'\phi')_0}}{w_s h}$$

EDMF--Eddy-Diffusivity Mass-Flux scheme
(Siebesma et al., 2007)

$$\overline{w'\phi'} = -K\frac{\partial\overline{\phi}}{\partial z} + M(\phi_u - \overline{\phi})$$

# Issues with the EDCG scheme

- The GFS EDCG scheme under-predicts the PBL growth for the convection-dominated (strongly unstable) PBL (Noh et al., 2003; Siebesma et al., 2007) .
- Siebesma et al. (2007) show that the underestimation of the daytime PBL growth EDCG is due to too weak entrainment flux at the PBL top which is caused by positive constant CG term over the entire column.

# EDMF PBL scheme

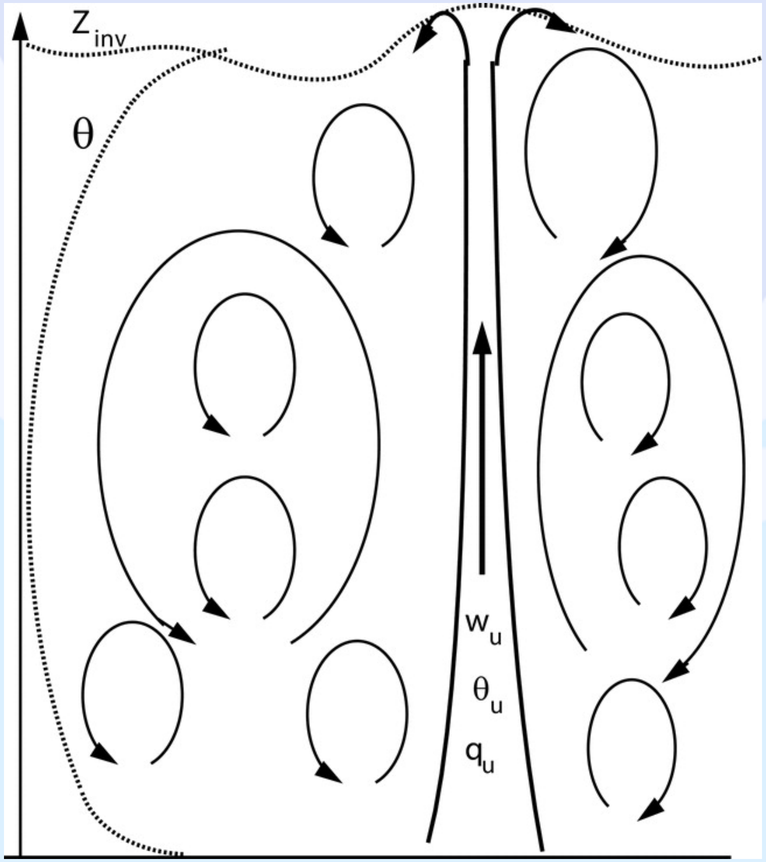



Fig. 1. Sketch of a convective updraft embedded in a turbulent eddy structure. (from Siebesma et al., 2007)

# EDMF PBL scheme

Updraft velocity equation:

$$\frac{\partial w_u^2}{\partial z} = -b_1 \varepsilon w_u^2 + b_2 g \frac{\theta_u - \bar{\theta}}{\bar{\theta}}$$

$b_1$=2.0, $b_2$=4.0
(Soares et al., 2004)

$$M = 0.1 w_u$$

Soares et al. (2004)

$$\frac{1}{M}\frac{\partial M}{\partial z} = \varepsilon - \delta$$

$$\frac{\partial (M\phi_u)}{\partial z} = (\varepsilon\bar{\phi} - \delta\phi_u)M$$

$$where \qquad \phi = s[c_p T + gz], q, u, v, ...$$

$$\varepsilon = c_e\left(\frac{1}{z+\Delta z} + \frac{1}{(h-z)+\Delta z}\right)$$

$c_e$=0.37, $h$: height of $w_u=0$

# EDMF PBL scheme

$$h = Rb_{cr} \frac{\theta_{va} |U(h)|^2}{g(\theta_v(h) - \theta_s)}$$

$Rb_{cr}$=0.25

EDCG:

$$\theta_s = \theta(z_1) + 6.5 \frac{\overline{(w'\theta')_0}}{w_s}$$

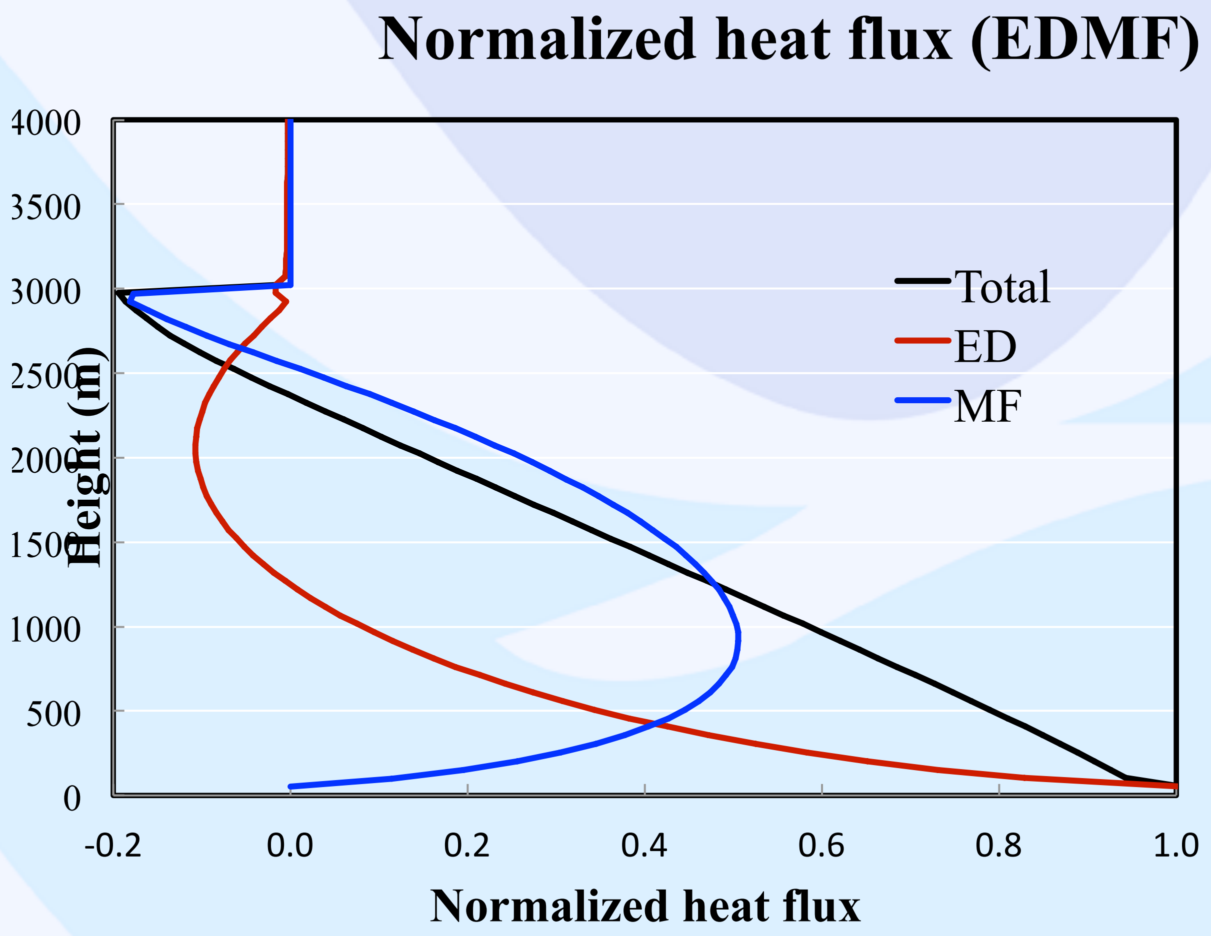
$h$ = height of zero heat flux

EDMF:

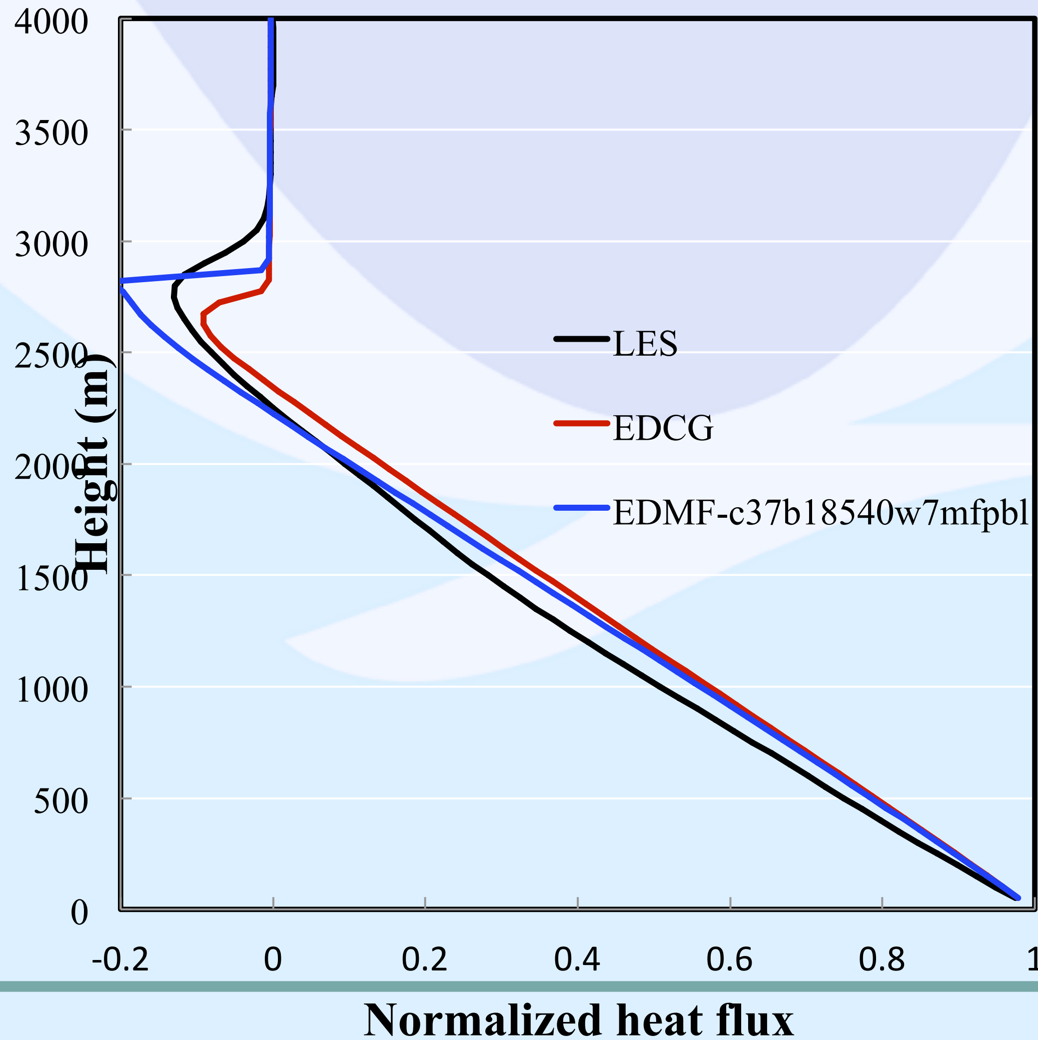
$\theta_s = \theta(z_1)$ for ED part

$h$=height of $w_u$=$0$ for MF part

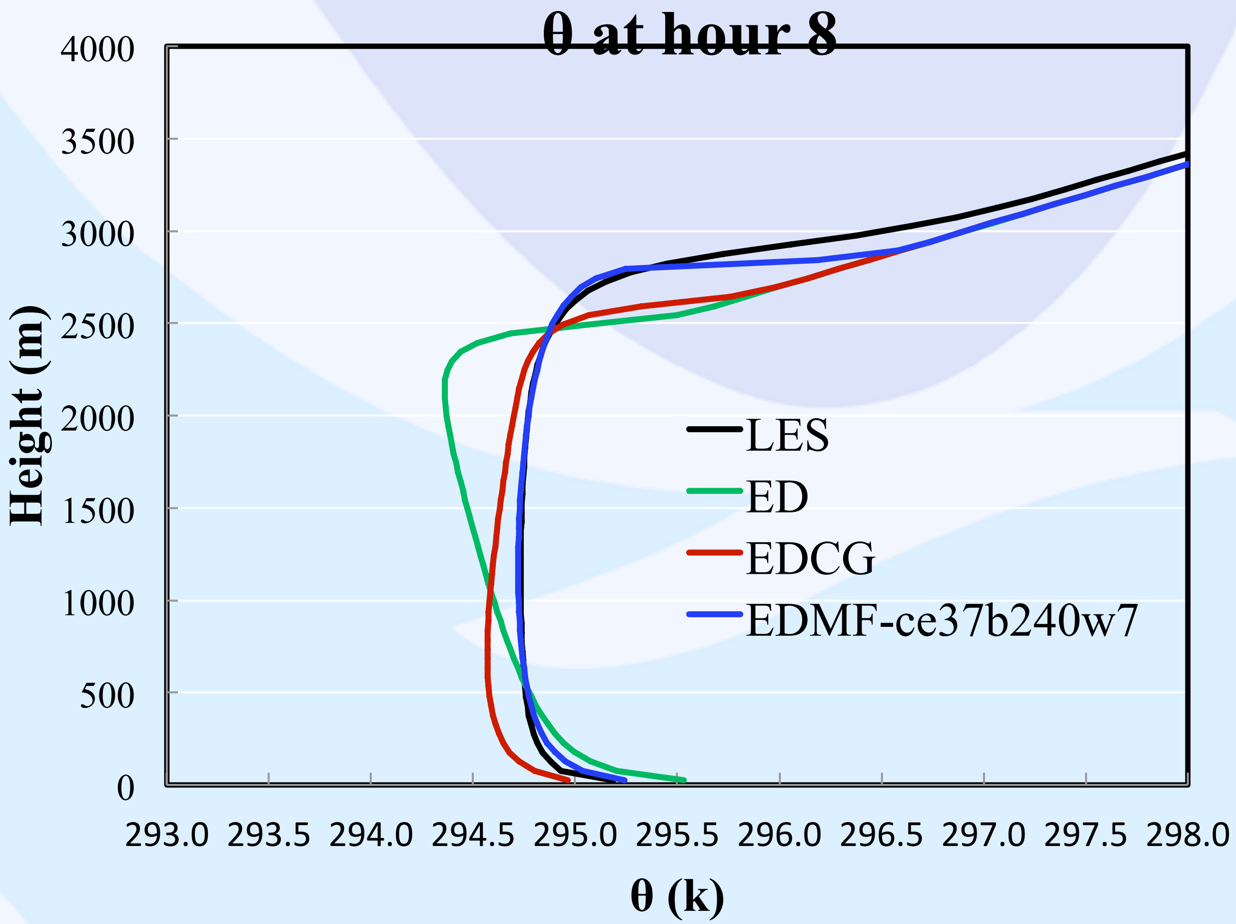
# SCM test with EDMF scheme



# SCM test with EDMF scheme



# SCM test with EDMF scheme



# EDMF scheme for momentum

• Include momentum mixing in the MF scheme with the effect of convection-induced pressure gradient force (Han & Pan, 2006)

$$\frac{\partial V_u}{\partial z} = -\varepsilon (V_u - \overline{V}) + c\frac{\partial \overline{V}}{\partial z}$$

c=0.55: effect of convection-induced pressure gradient force

# Development of a hybrid EDMF PBL scheme

- A hybrid EDMF scheme is developed, where the EDMF scheme is applied only for the strongly unstable PBL (i.e., CBL), while the EDCG scheme is used for the weakly unstable PBL.
- The rationale for the hybrid scheme is that the MF scheme works well for the cases with coherent, well-organized updrafts, such as cumulus convection and strong thermals in CBL, whereas it may not work well for the weakly unstable PBL where the larger eddies easily break into smaller ones and hardly maintain a coherent structure.
- The z/L (where L is Monin-Obukov length) is used for the criteria for the CBL (currently, *convective* for $z/L < -0.5$ [Sorbjan, 1989])
- The Tropics are largely occupied with ocean where a strongly unstable PBL is hardly found. Therefore, the EDCG scheme is mostly called over the Tropics in the hybrid scheme.

# Stable boundary layer (SBL)

Before July 2010, a K-profile method is used for the vertical turbulent mixing in the SBL, which has been reported to give too much vertical diffusion (e.g., CASES99)

$$K_m = \kappa w_s z \left(1 - \frac{z}{h}\right)^2$$

In July 2010 upgrade, therefore, a local scheme is used for the SBL to reduce vertical diffusion

$$K_{m,h} = l^2 f_{m,h}(Ri) \left|\frac{\partial U}{\partial z}\right|$$

After that it was noticed that the diffusion in the SBL is too weak. The scheme is modified to uses the above local scheme for the strongly stable condition (z/L > 0.2) where the turbulence is often sporadic, whereas it adopts the K-profile method but with a varying critical bulk Richardson number for the weakly and moderately stable condition (z/L < 0.2) where turbulence is continuous.

$$h = Rb_{cr} \frac{\theta_{va} |U(h)|^2}{g(\theta_v(h) - \theta_s)} \qquad Rb_{cr} = 0.16\left(10^{-7} R_0\right)^{-0.18} \qquad R_0 = \frac{U_{10}}{f_0 z_0}$$

Vickers & Mahrt (2004)

$Rb_{cr} = min(max(Rb_{cr}, 0.15), 0.35)$

# Stratocumulus-top driven turbulence mixing (Follow Lock et al., 2000)

$$\overline{w'\theta'} = -\left(K_h^{surf} + K_h^{Sc}\right)\frac{\partial\overline{\theta}}{\partial z} + K_h^{surf}\gamma_h$$

$$K_h^{Sc} = 0.85\kappa V_{Sc}\frac{(z - z_b)^2}{h_b - z_b}\left(1 - \frac{z - z_b}{h_b - z_b}\right)^{1/2}$$

$$V_{Sc}^3 = \frac{g}{\theta_0}(h_b - z_b)\Delta R/(\rho c_p)$$

(Buoyancy reversal term is neglected)

$$-\overline{(w'\theta_v')}_{h_b} = c\frac{\Delta R}{\rho c_p} \qquad c=0.2$$

(Moeng et al., 1999)

$$if\ c_p\Delta\theta_e / L\Delta q_t > 0.7, \quad c=1.0$$

(CTEI condition; MacVean and Mason, 1990)

# Parameterization of TKE dissipative heating

Viscous dissipation of turbulence kinetic energy (TKE)

Heat

$$\varepsilon \Rightarrow c_p \frac{\partial \overline{T}}{\partial t}$$

Viscous dissipation of turbulent kinetic energy (TKE) can be a significant source of heat especially in strong wind conditions such as hurricanes (e.g., Bister & Emanuel, 1998), while its effect is not taken into account in the current operational GFS.

# Parameters control the PBL scheme

The following parameters can be set through configure files:

- dspheat = .true. : use TKE dissipative heating
- hybedmf = .true.: use hybrid EDMF PBL scheme.

Thankyou!!

backup

# Future PBL scheme
# -Scale-aware TKE-based Moist EDMF

- Scale-aware TKE-based Moist Eddy-Diffusivity Mass-Flux (EDMF) Parameterization for Vertical Turbulent Mixing with Interaction with Cumulus Convection (Jongil Han and Chris Bretherton)
  - EDMF is applied to both weakly and strongly unstable PBL
  - TKE equation is added. Eddy diffusivity is calculated based on the TKE and mixing length.
  - Shear and buoyancy production terms of TKE are strongly influenced by the mass flux (MF) term.
  - Bougeault & Lacarrere (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.
  - MF method is used to parameterized the stratocumulus-top-driven turbulence mixing
  - For updraft or downdraft parcel properties in condensation, moist adiabatic process is considered and the liquid water potential temperature $?_l$ and total water $q_T = q + q_l$ are used, which are conserved in both dry and moist adiabatic processes
  - Scale-aware parameterization is added to the MF terms
  - Interaction between TKE and cumulus convection is included
  - EDMF frame can potentially unify PBL and shallow and deep convection.

# Future PBL scheme
# -Simplified Higher-Order Closure

- Simplified Higher-Order Closure **(SHOC)** is an assumed PDF method
- Second-order moments are diagnosed using simple formulations based on Redelsperger and Sommeria (1986) and Bechtold et al. (1995)
- Third-order moment is diagnosed using algebraic expression of Canuto et al. (2001)
- All diagnostic expressions for the higher order moments are a function of SGS turbulent kinetic energy.
- A prognostic TKE equation is added for SHOC.
- The dissipation term uses a new formulation for the general turbulence length scale, L, that is specified separately for the boundary layers and the cloudy layers.
- Using turbulence length scale, L, and SGS TKE, e, SHOC can obtain turbulent mixing coefficient: K = -0.1L*sqrt(e)
- Remaining terms are parametrized as downgradient diffusion for TKE using the turbulent mixing coefficient K.
- SHOC can potentially combine macrophysics, PBL, and shallow convection.

# Summary (1)

- The EDMF scheme well predicts the CBL growth compared to a large-eddy simulation result and improves precipitation forecast skill especially for light rain by destroying unrealistic cloud water accumulation near the CBL top.
- A hybrid EDMF PBL scheme is developed, where the EDMF scheme is applied only for the strongly unstable PBL, while the EDCG scheme is used for the weakly unstable PBL.
- Compared to the full EDMF scheme, the hybrid scheme significantly reduces the tropical wind vector RMSE, while it maintains the improvements of the skills for precipitation forecast for light rain and 500mb height forecast.
- Inclusion of TKE dissipative heating improves the GFS atmospheric energy budget and the hurricane intensity forecast, whereas its impact on the GFS forecast skill is negligibly small.

# Summary (2)

- The hybrid EDMF scheme shows a mixed signal for the hurricane track forecast, which is improved in Atlantic Ocean but degraded in East Pacific Ocean.
- The parameters optimized for the current operational GFS vertical resolution (lower resolution), which has weaker mass-flux mixing compared to those optimized for higher vertical resolution, further improve the forecast skill for 500mb height, tropical wind vector, and East Pacific hurricane track, but in the expense of reduced improvement in precipitation forecast for light rain.
- Tests with higher resolution (T1534: ~13 km) and data assimilation is underway for the next GFS implementation.

# Mininq (EDCG)

# Vertical mixing scheme in FV3GFS (moninq)

- It is a first order K-theory-based scheme under down-gradient diffusion assumption, where K is eddy-diffusivity.
- For the daytime planetary boundary layer (PBL), an eddy-diffusivity (profile) counter-gradient (EDCG) mixing approach is adopted to take into account nonlocal transport by strong updraft.
- For the vertical diffusion in nighttime stable boundary layer and layers above PBL, a local K is used (which is a function of local gradient Richardson number, local wind shear, and a mixing length).
- Include stratocumulus-top driven turbulence mixing based on Lock et al.'s (2000) study.
- Enhance stratocumulus top driven diffusion when the condition for cloud top entrainment instability is met.

# EDCG approach for unstable PBL (moninq)

$$\overline{w'\theta'} = -K_h^{surf}\left(\frac{\partial\theta}{\partial z} - \gamma_h\right) \qquad K_m^{surf} = \kappa w_s z\left(1 - \frac{z}{h}\right)^2$$

$$K_h^{surf} = \Pr^{-1} K_m^{surf} \qquad \Pr = \frac{\Phi_h}{\Phi_m} + b\alpha\kappa$$

$$w_s = \left(u_*^3 + 7\alpha\kappa w_*^3\right)^{1/3} \qquad \gamma_h = 6.5\frac{\overline{(w'\theta')_0}}{w_s h}$$

# PBL height ($h$) in unstable BL (moninq)

- Daytime PBL grows by surface heating and entrainment flux at the PBL top.
- $h$ is intentionally enhanced with a thermal excess to have an implicit entrainment flux at the PBL top

$$h = Rb_{cr} \frac{\theta_{va} |U(h)|^2}{g(\theta_v(h) - \theta_s)}$$

$Rb_{cr}$=0.25

$$\theta_s = \theta(z_1) + 6.5 \frac{\overline{(w'\theta')_0}}{w_s}$$

$h$ = height of zero heat flux, not that of minimum heat flux

# Diffusion in the stable boundary layer and the layers above the PBL (Moninq)

- Use a local diffusion scheme (Louis, 1979)

$$\overline{w'\theta'} = -K_h \frac{\partial \theta}{\partial z} \qquad K_{m,h} = l^2 f_{m,h}(Ri)\left|\frac{\partial U}{\partial z}\right| \qquad Ri = \left(\frac{g}{T}\right)\frac{\partial \theta_v}{\partial z} \Big/ \left(\frac{\partial U}{\partial z}\right)^2$$

$$f_h(Ri) = \frac{1}{(1+5Ri)^2} \qquad \Pr = 1 + 2.1Ri$$

Stable condition

$$f_h(Ri) = 1 + \frac{8|Ri|}{1+1.286|Ri|^{1/2}}$$

$$f_m(Ri) = 1 + \frac{8|Ri|}{1+1.746|Ri|^{1/2}}$$

Unstable condition

$$\frac{1}{l} = \frac{1}{kz} + \frac{1}{l_0}$$

$l_0 = 150\ m$ for unstable condition

$30\ m$ for stable condition

# Stratocumulus-top driven turbulence mixing (moninq)

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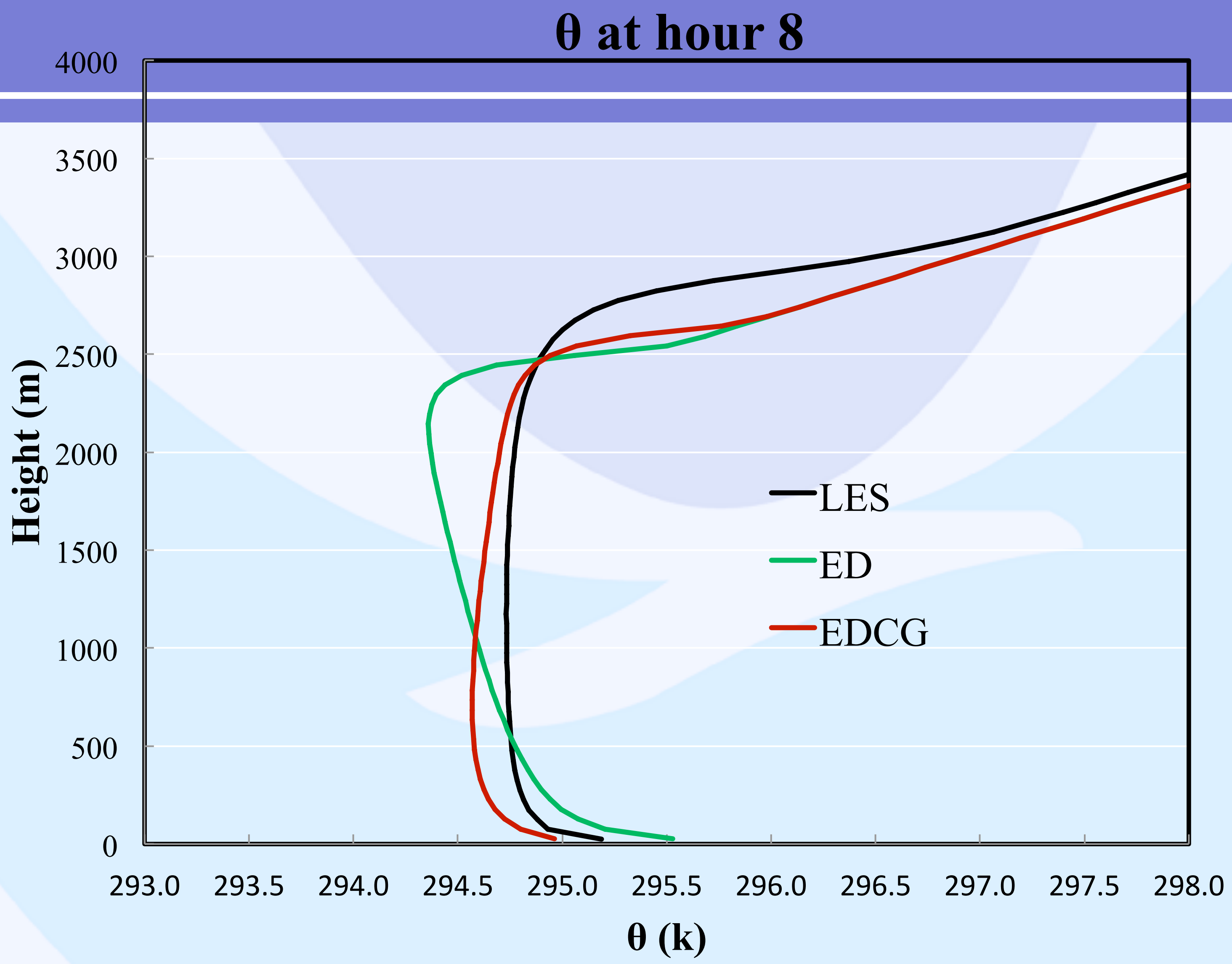
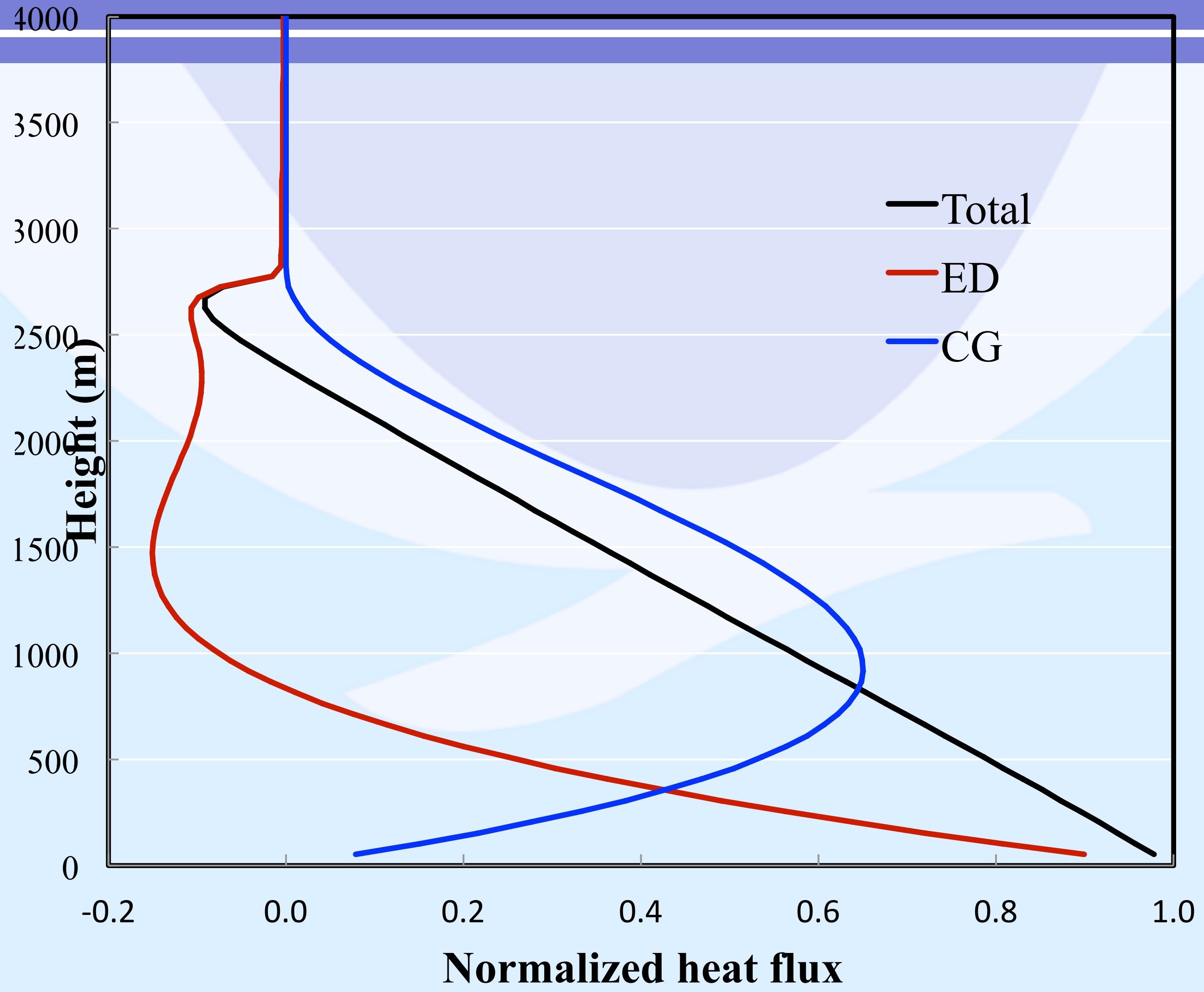


θ at hour 8
4000
3500
3000
2500
2000
1500
1000
500
0
Height (m)
LES
ED
EDCG
293.0
293.5
294.0
294.5
295.0
295.5
296.0
296.5
297.0
297.5
298.0
θ (k)

# Normalized heat flux (EDCG)



# Normalized heat flux at hour 8