Summer School “**Severe Convective Weather: Theory and Applications**”
Lecce, Italy, September 2012

# I. Conceptual Introduction to Atmospheric Planetary Boundary Layers


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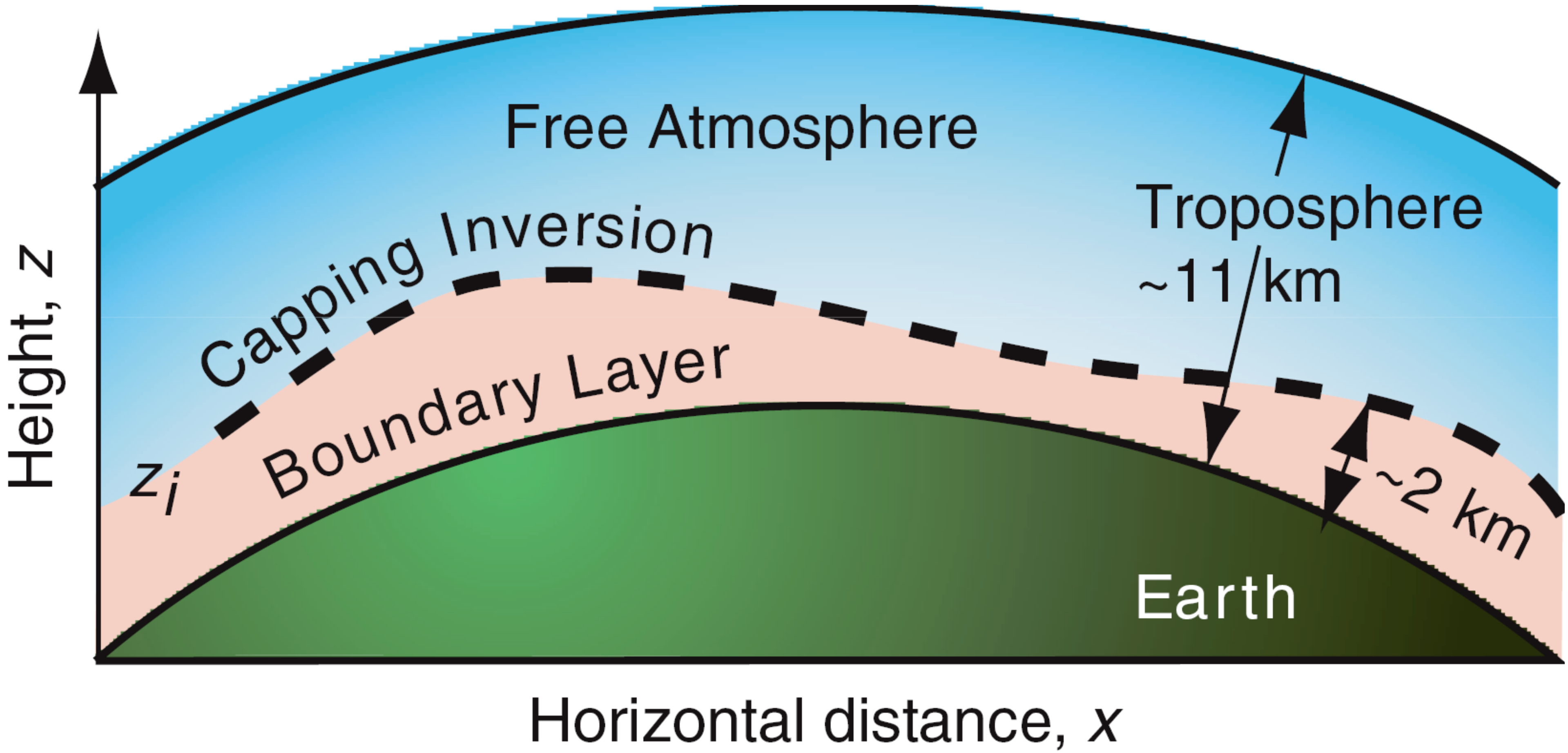
# Outline

- Place and role of planetary atmospheric boundary layer (ABL) in Earth's atmosphere;
- Effects of temperature/density stratification in the ABL;
- Diurnal cycle of the ABL;
- Structure of convective, neutral, and stably stratified (stable) ABLs;
- Interactions of ABL with underlying surfaces;
- Interactions between ABL and free atmosphere.

# Place of planetary ABL in Earth's atmosphere

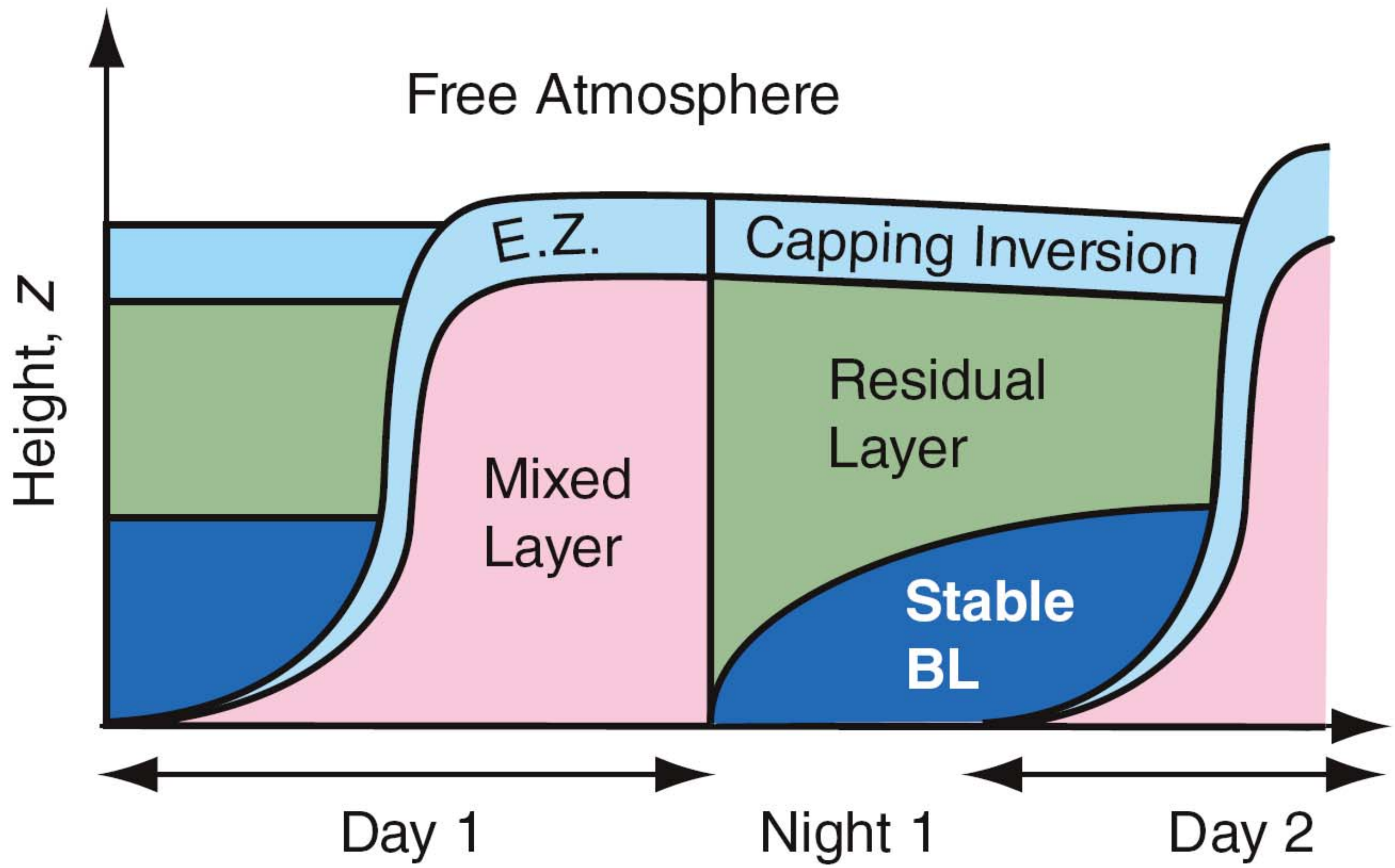


# Planetary ABL flows

**conflate four major nasty features of geophysical flows:**

**(i) turbulence,** **(ii) density stratification,**

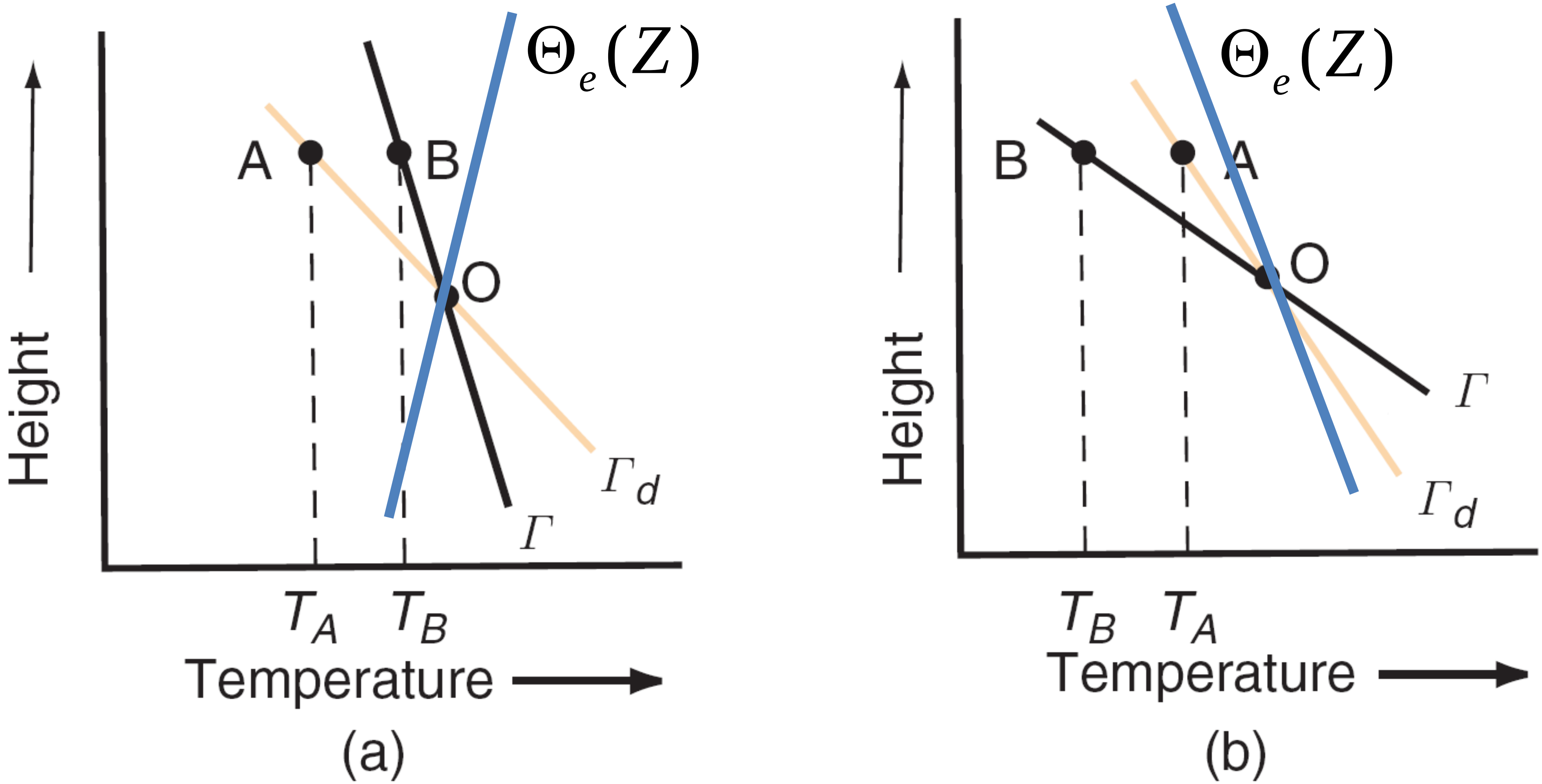
**(iii) rotation,** **(iv) thermal forcing.**




after Roland Stull

# Effect of stratification in atmosphere

Wallace and Hobbs (2006)

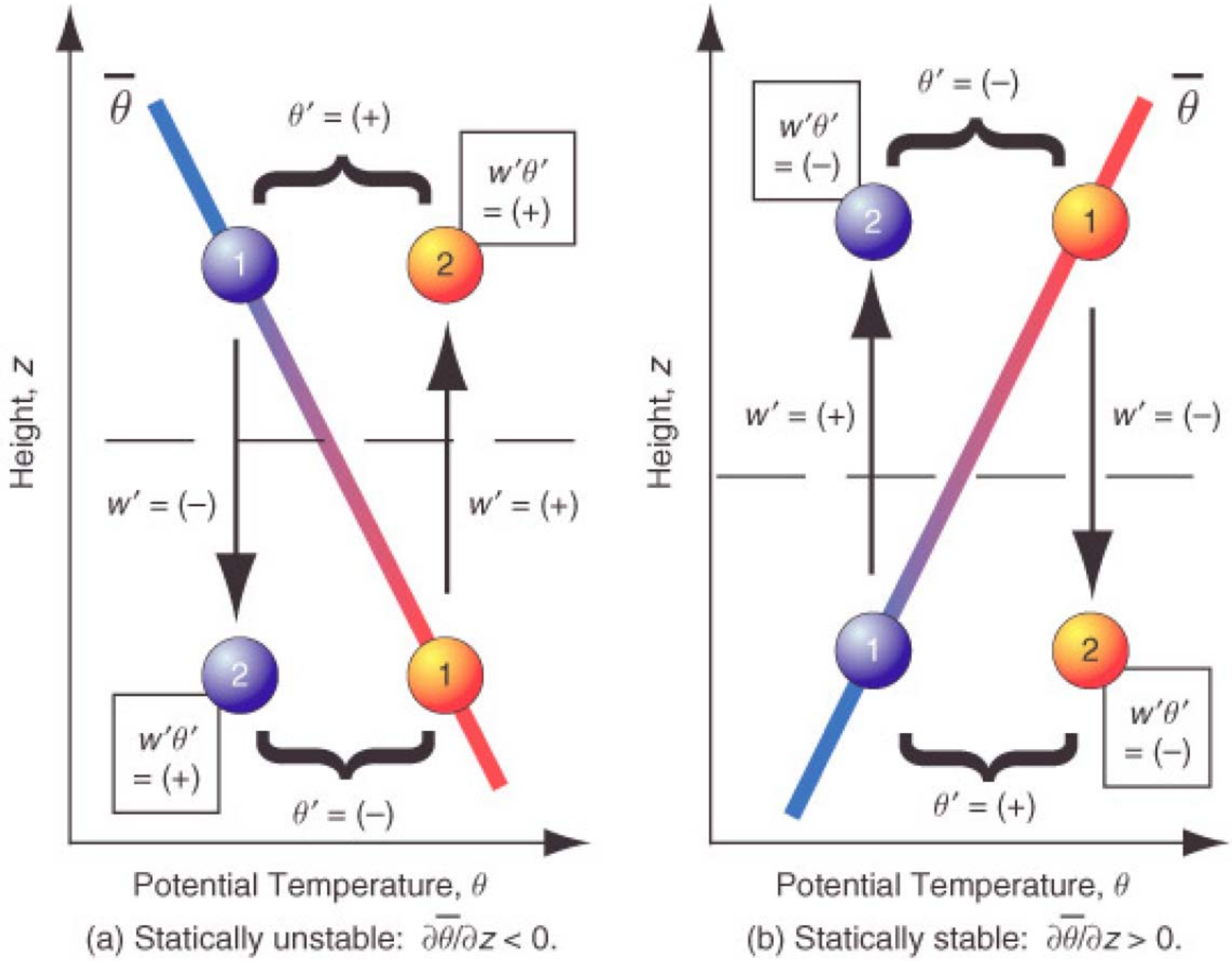



$\Gamma = -dT_e / dZ$ (normally $> 0$) and $\Gamma_d = -\left(dT / dZ\right)_{\text{adiab}} = g / c_p$

$$d\Theta_e / dZ \approx dT_e / dZ + \Gamma_d = -\Gamma + \Gamma_d$$

$d\Theta_e / dZ > 0$ **stable** $\qquad$ $d\Theta_e / dZ < 0$ **unstable**

# Heat exchange in ABL flows



# ABL stability parameters

**Convenient variable to account for combined effect of heat and moisture on static stability is buoyancy**

$$b = g(\theta_v - \theta_{vr}) / \theta_c ,$$

**where** $\theta_v \simeq \theta + 0.61\theta_c q$ **is the virtual potential temperature.**

**(Turbulent vertical kinematic) buoyancy flux is** $\overline{w'b'}$.

**Commonly used stability parameters:**

$\zeta = z / L$, **where** $L = -\dfrac{(-\overline{u'w'})^{3/2}}{\kappa \overline{w'b'}}$ **is Obukhov length (scale).**

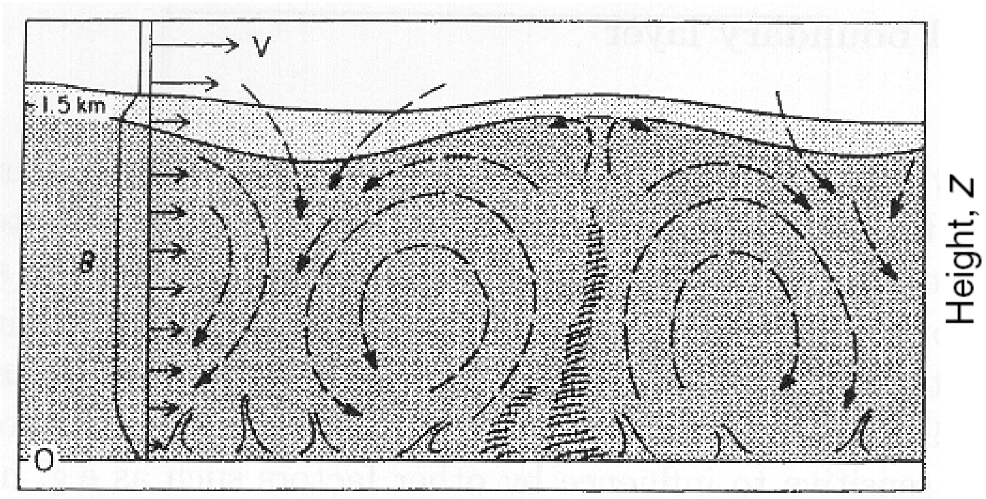
**Flux Ri number** $\mathrm{Ri}_f = \dfrac{\overline{w'b'}}{\overline{u'w'}(\partial \bar{u} / \partial z)}$, **gradient Ri number** $\mathrm{Ri} = \dfrac{\partial \bar{b} / \partial z}{(\partial \bar{u} / \partial z)^2}$

**represent ratio of buoyancy to shear turbulence production rates.**

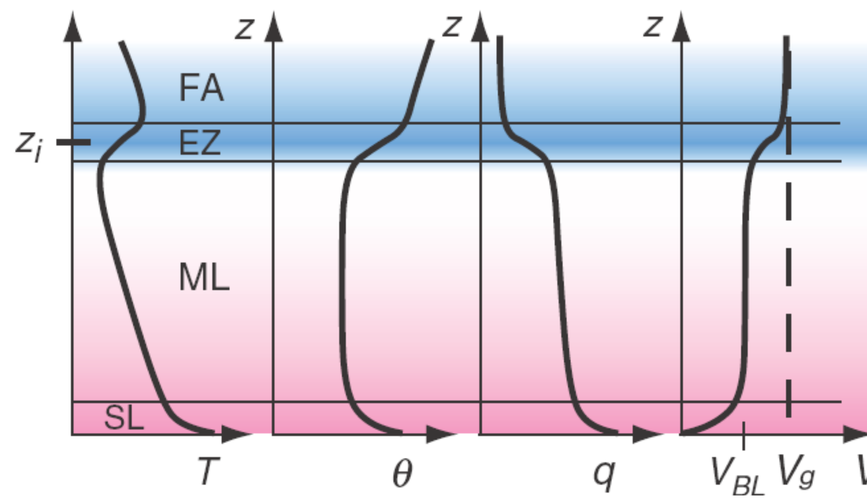
$$\frac{\mathrm{Ri}}{\mathrm{Ri}_f} = \mathrm{Pr}_t = \frac{\varphi_h}{\varphi_m}, \qquad \mathrm{Ri} = \frac{\mathrm{Pr}_t}{\varphi_m}\zeta, \qquad \mathrm{Ri}_f = \frac{\zeta}{\varphi_m} = \frac{\mathrm{Pr}_t}{\varphi_h}\zeta .$$

# Daytime convective boundary layer (CBL)

## In its dry version: a turbulent boundary layer primarily driven by heating from below with a secondary wind-shear forcing



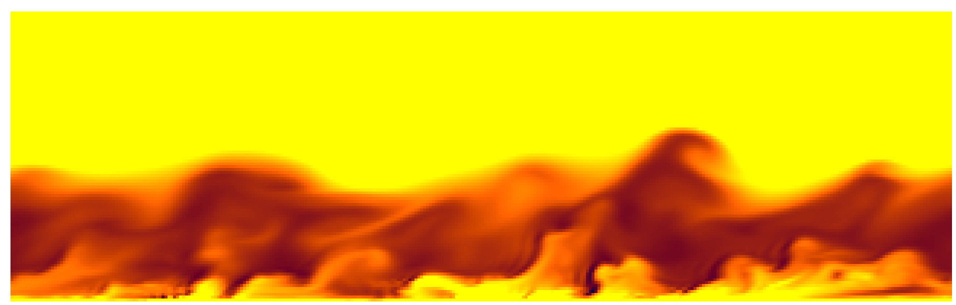

after John Wyngaard




after Roland Stull

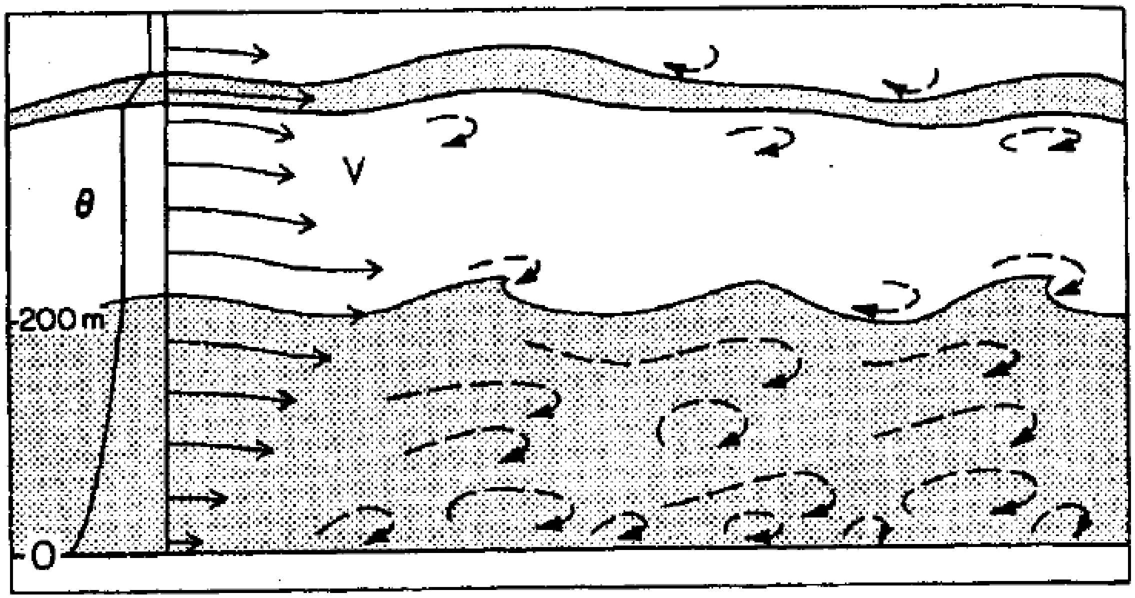
Potential temperature field in the inversion-capped CBL (DNS visualization)

**CBL without wind shear**



**CBL with wind shear**

# Conventional nocturnal stable ABL (SBL)

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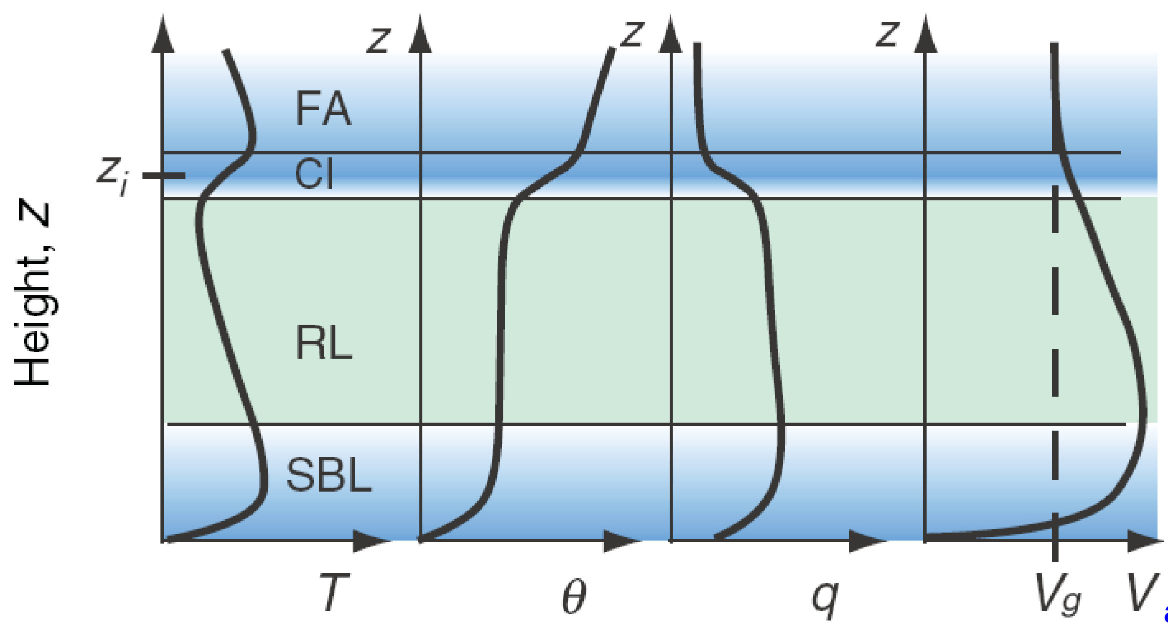



after Roland Stull

# Surface energy balance components

## Sensible heat flux:

$$F_H = \rho c_p \overline{w'\theta'} \equiv \rho c_p Q_z.$$

## Latent heat flux:

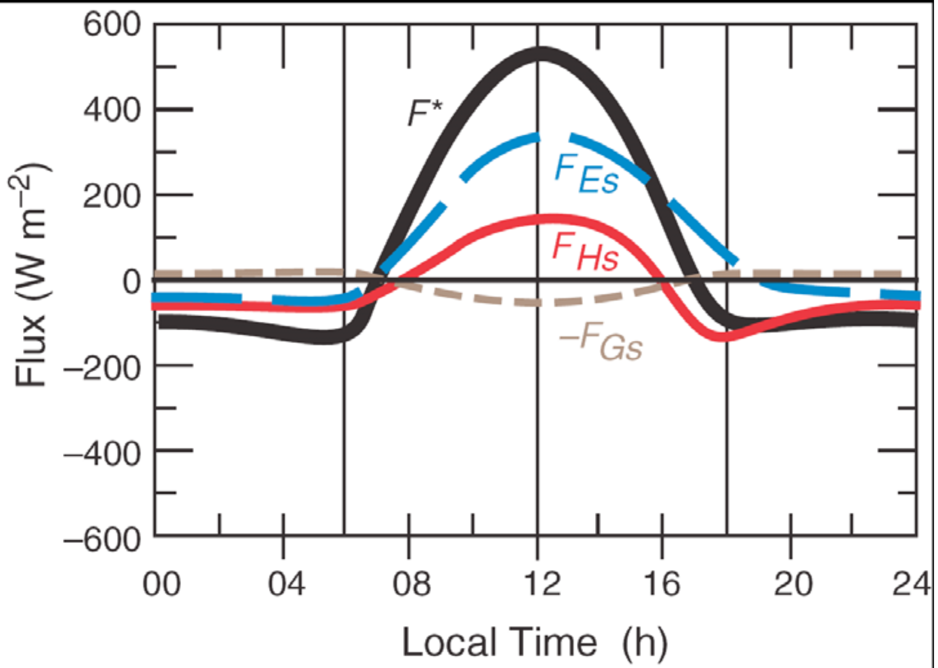
$$F_L = L_v E = L_v \rho \overline{w'q'} \equiv L_v \rho D_z.$$

### Approximate form of surface (*s*) energy budget:

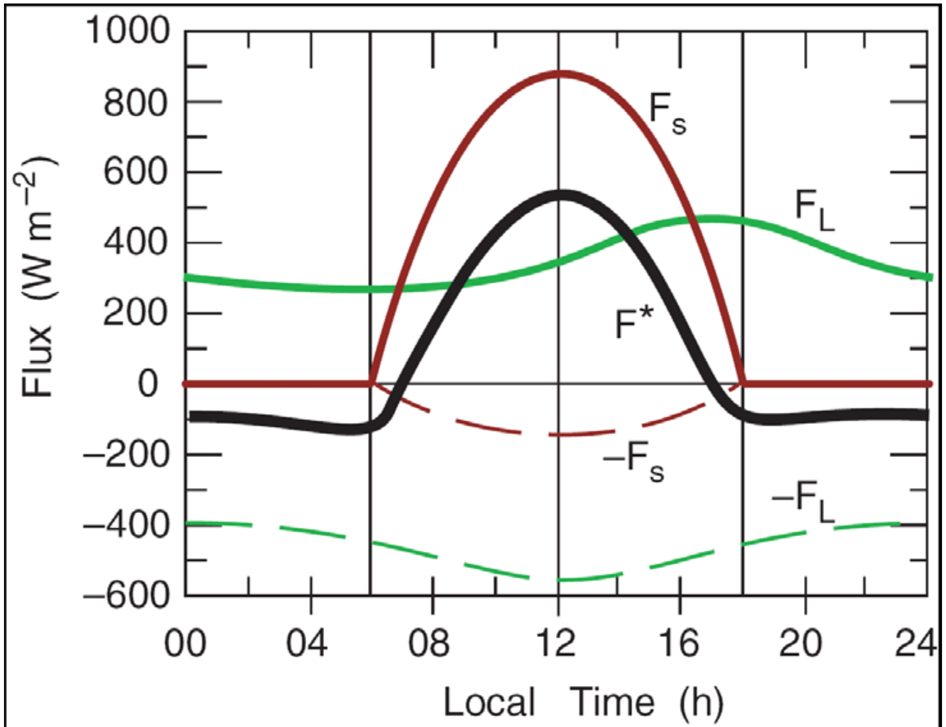
$$F^* = F_{Hs} + F_{Es} + F_{Gs}.$$

$F^*$ - **surface net radiative flux**; $F_G$ - **ground heat flux**.

# Surface energy balance







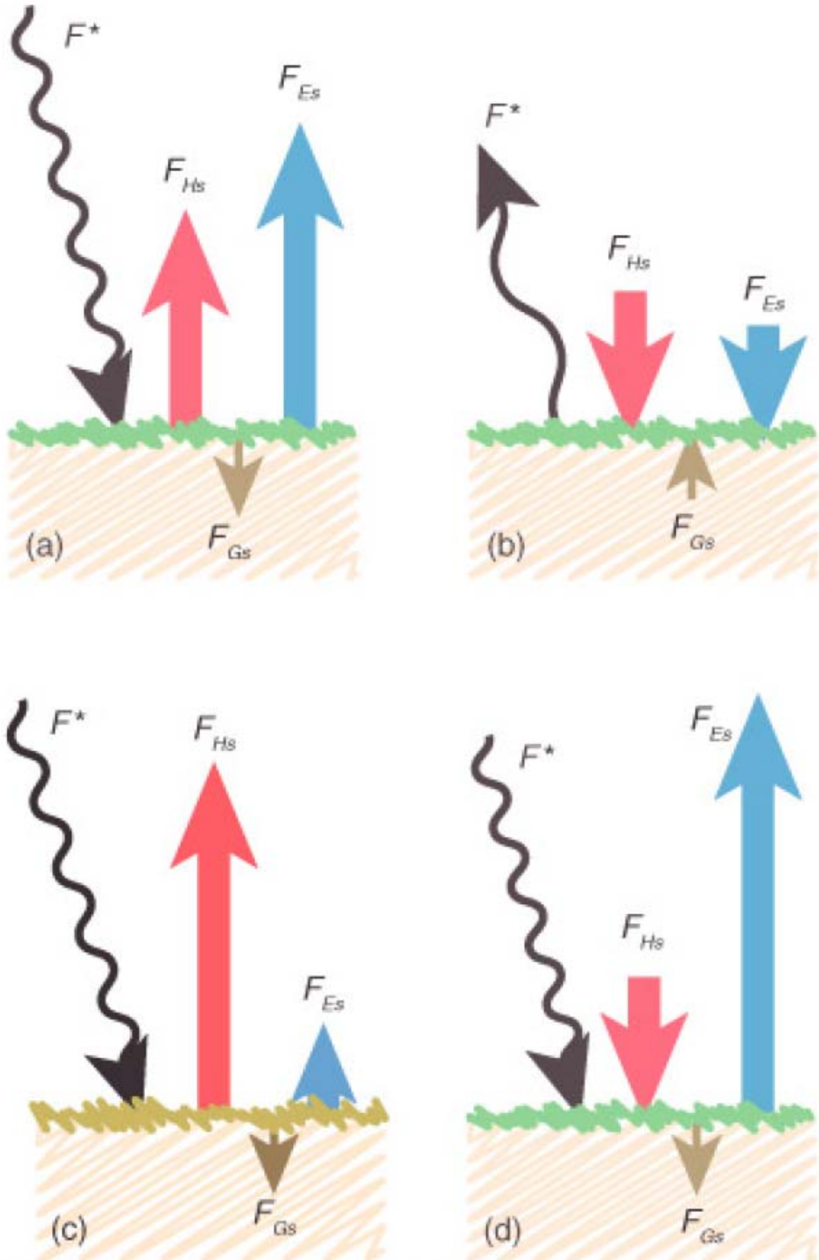

## Energy balance

$$F^* = F_{Hs} + F_{Es} + F_{Gs}$$

## Radiation balance

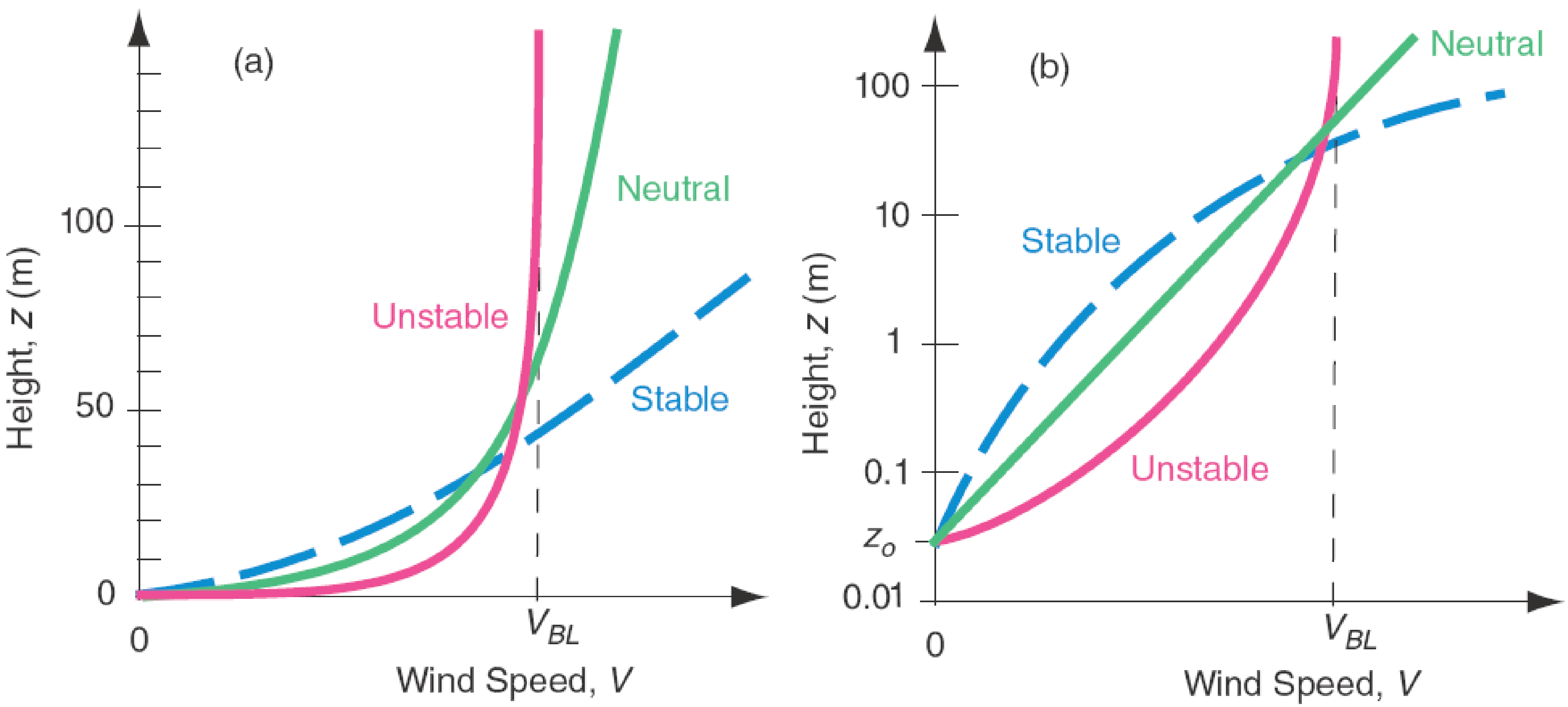
$$F_s^{\downarrow} - F_s^{\uparrow} + F_L^{\downarrow} - F_L^{\uparrow} = F^*$$

# Possible surface energy balance scenarios




From *Meteorology for Scientists and Engineers* by R. Stull (2000)

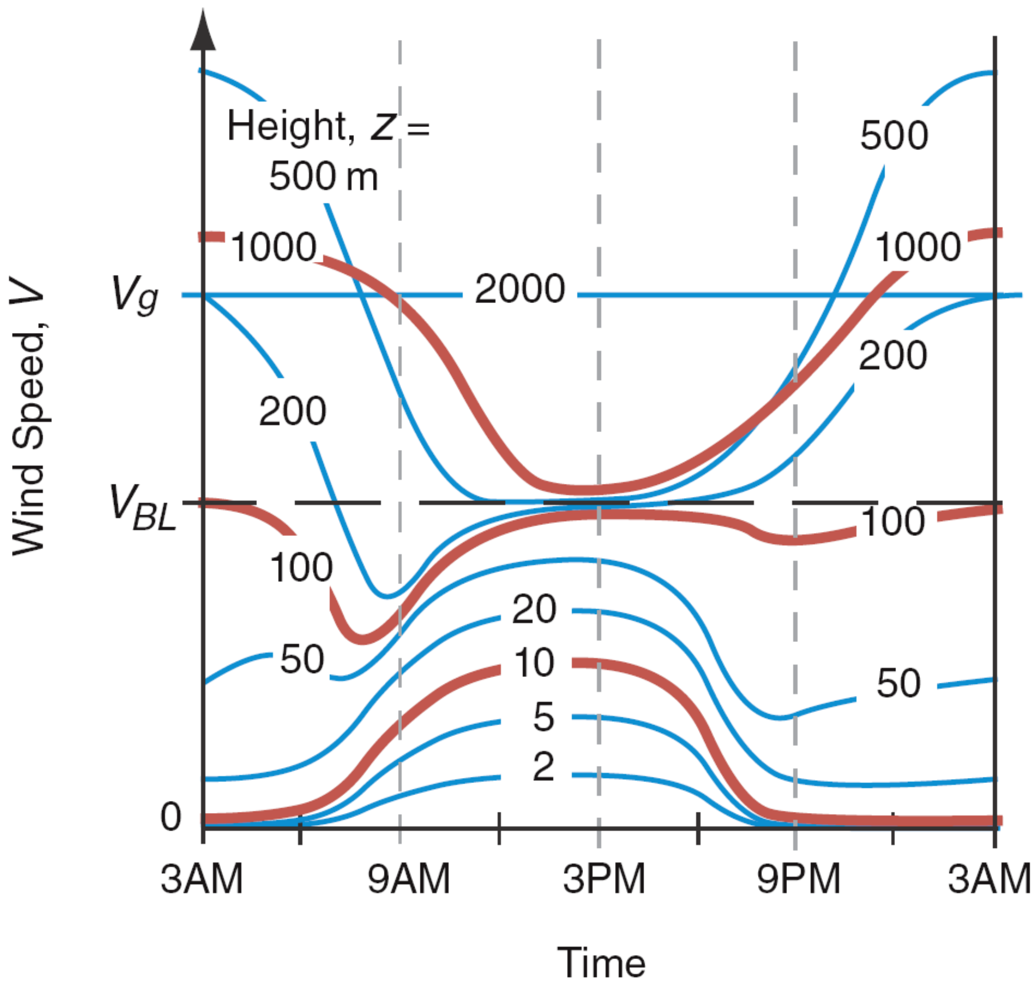
# Effect of stability of wind variation with height in the lower portion of ABL



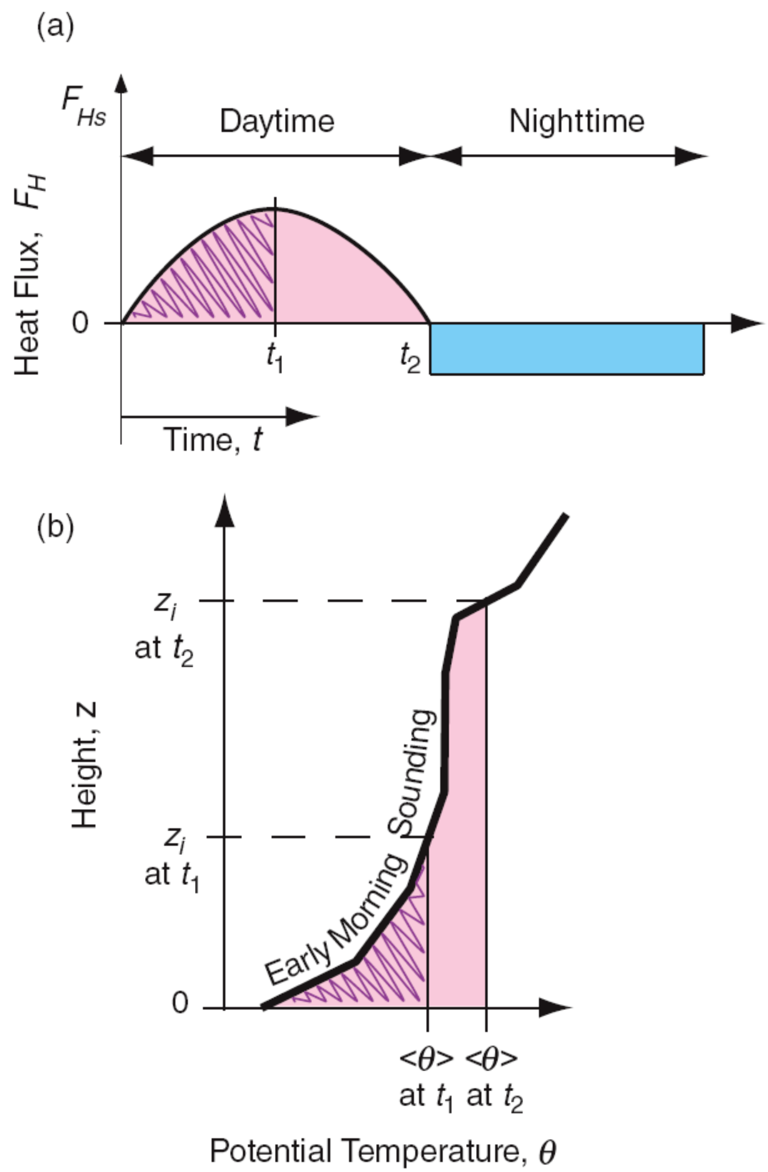

linear *z*　　　　log *z*

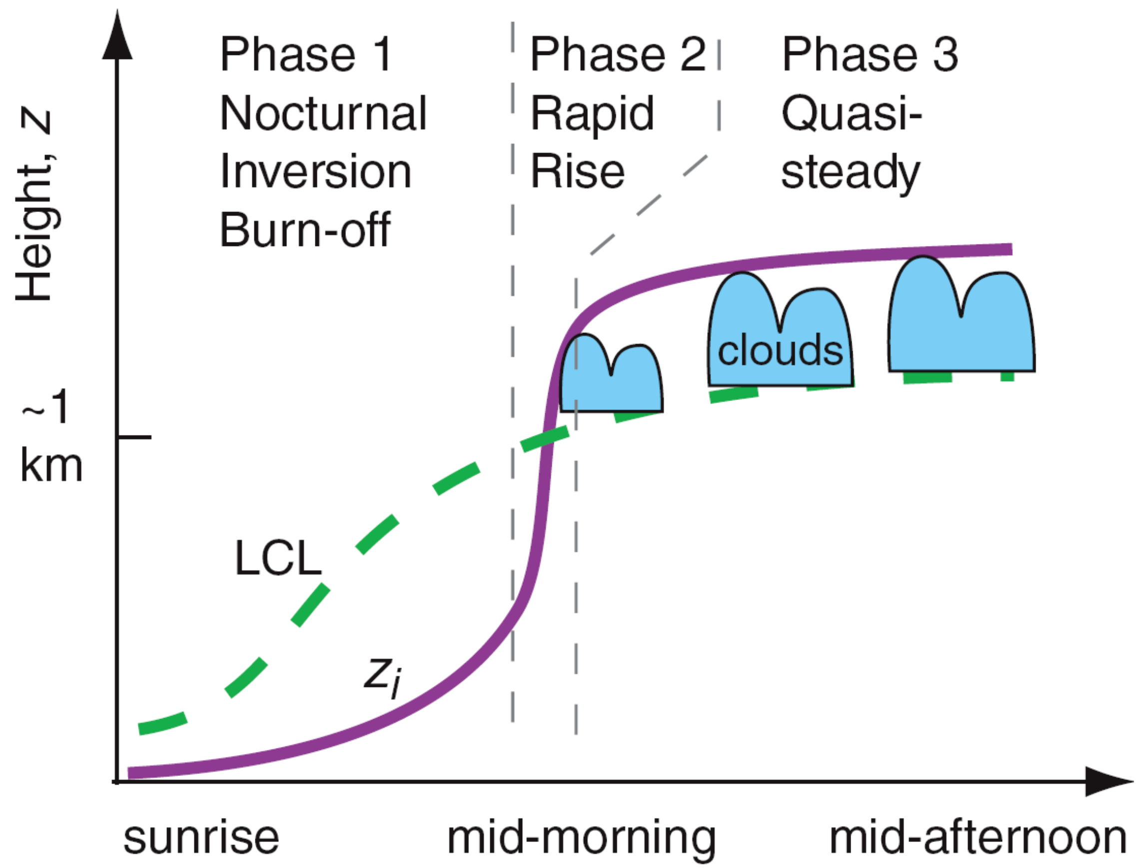
From *Meteorology for Scientists and Engineers* by R. Stull (2000)

# Variation of wind speed with local time in ABL over land



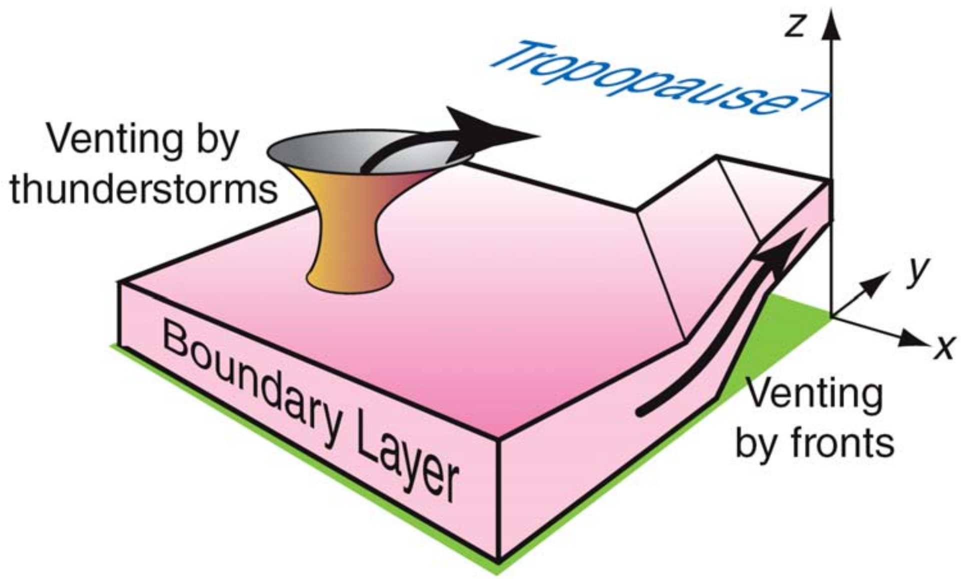
# Development of CBL




Adapted from R. B. Stull, An *Introduction to Boundary Layer Meteorology*, Kluwer Academic Publishers, Dordrecht, The Netherlands, 1988, Fig. 11.10, p. 452, and Fig. 13.12, p. 564, Copyright 1988 Kluwer Academic Publishers, with kind permission of Springer Science and Business Media.

# ABL interaction with free atmosphere

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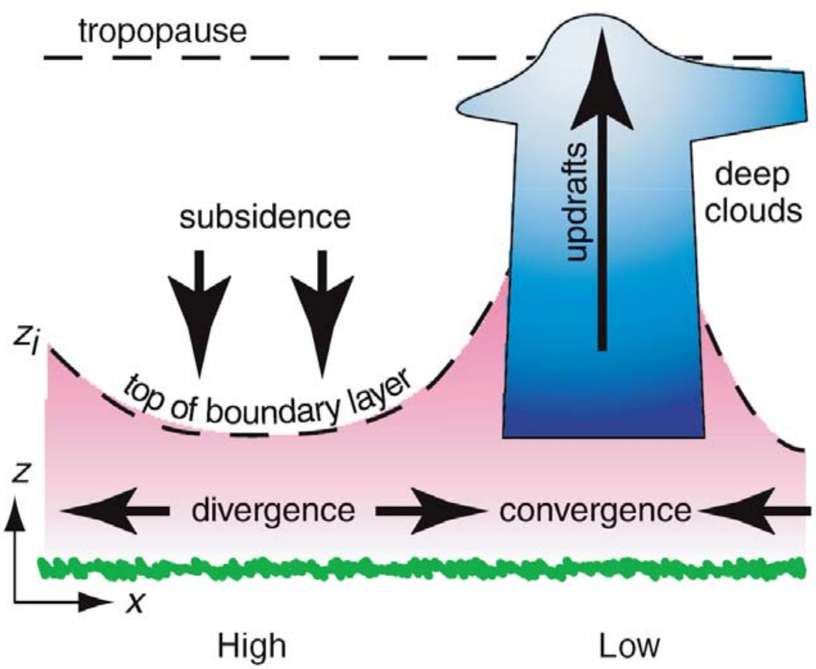
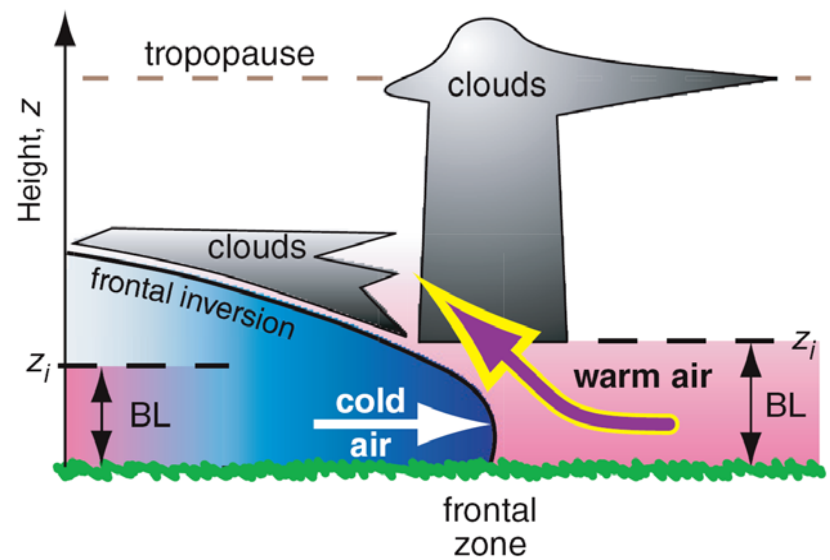
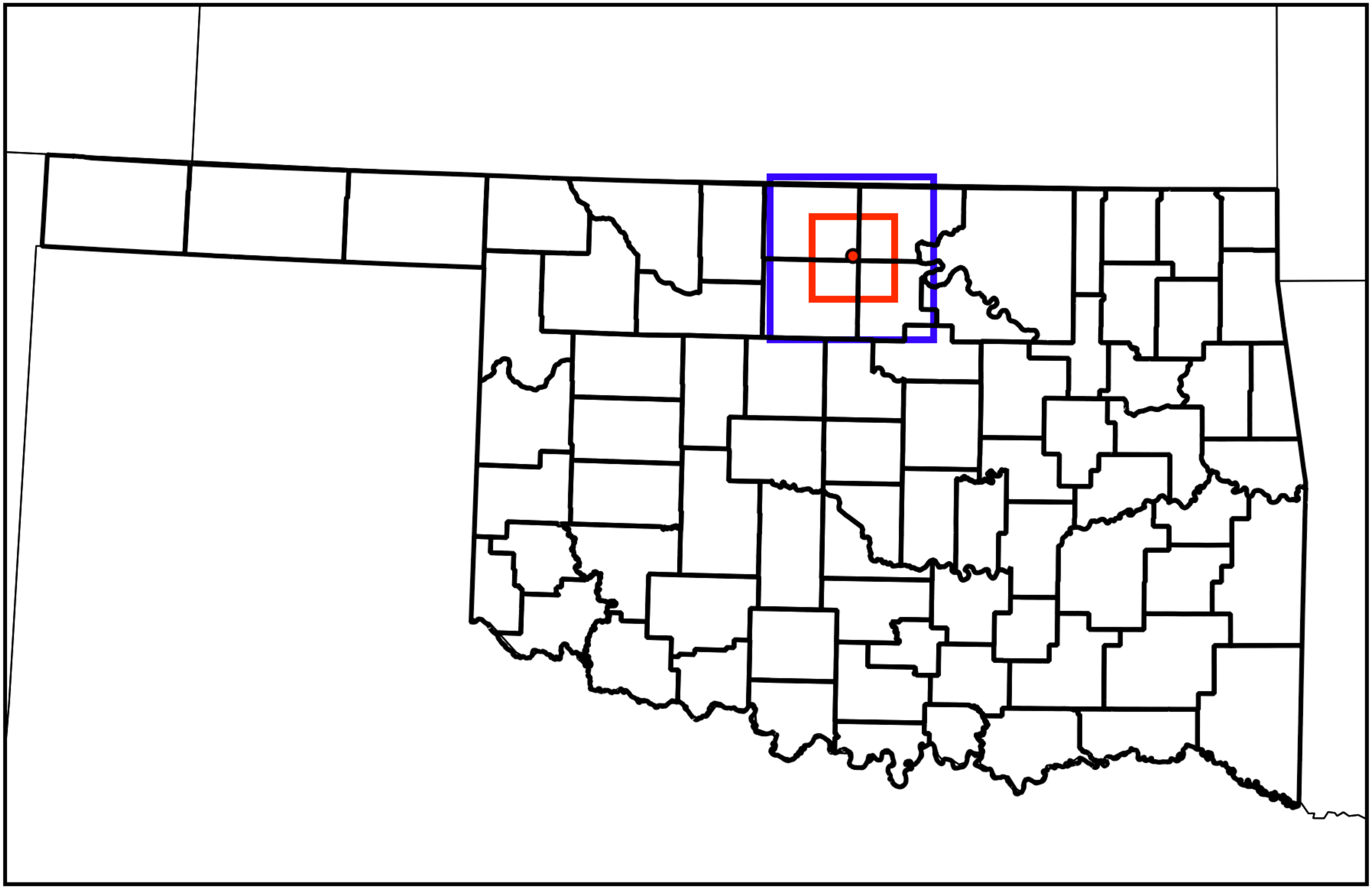


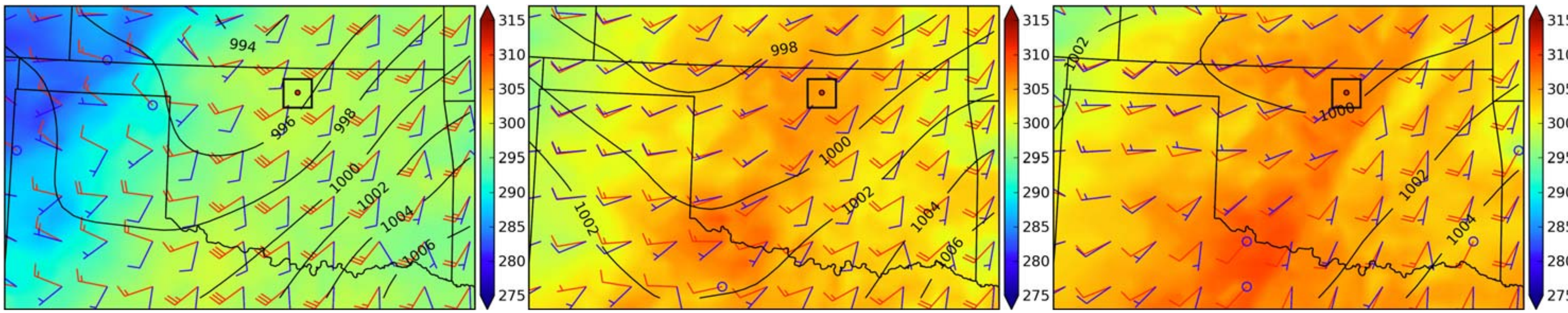



# CBL development in evolving atmosphere: model study

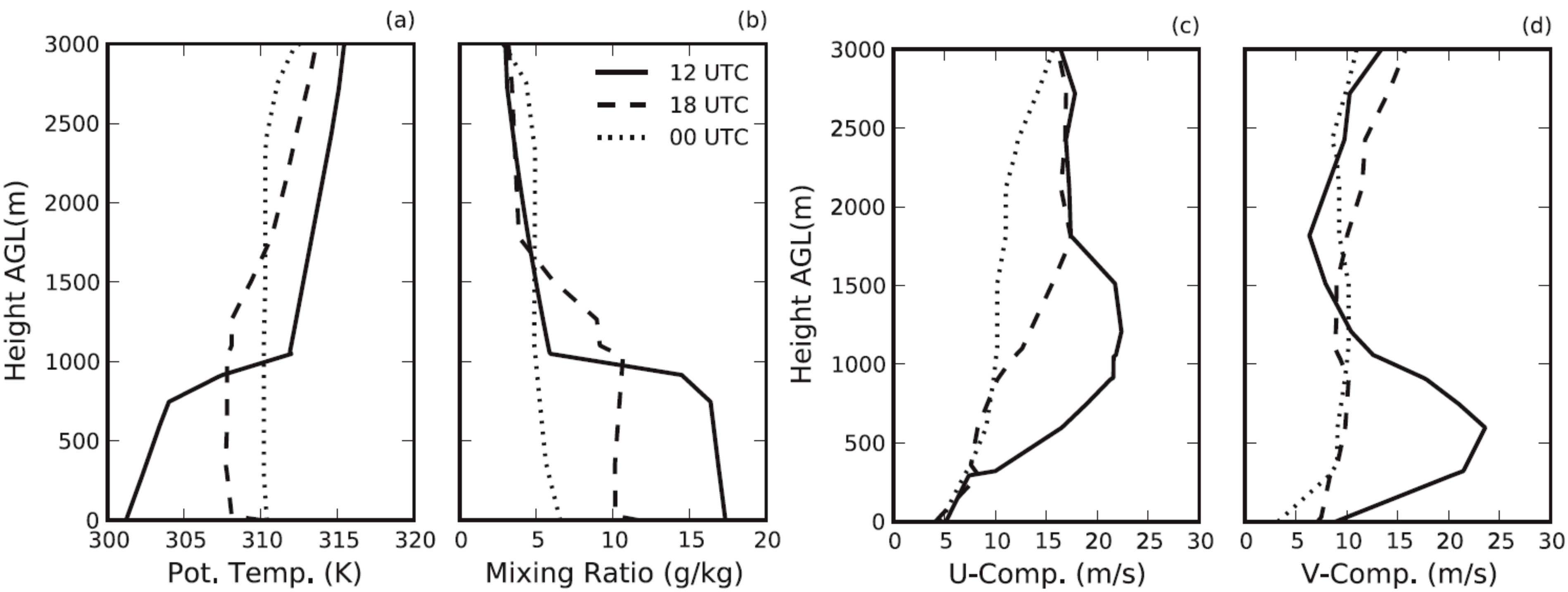
Gibbs et al. (2011)



# CBL development in a dryline environment



**12 UTC** 06/07/2007 **18 UTC** 06/07/2007 **00 UTC** 06/08/2007



# CBL structure in a dryline environment

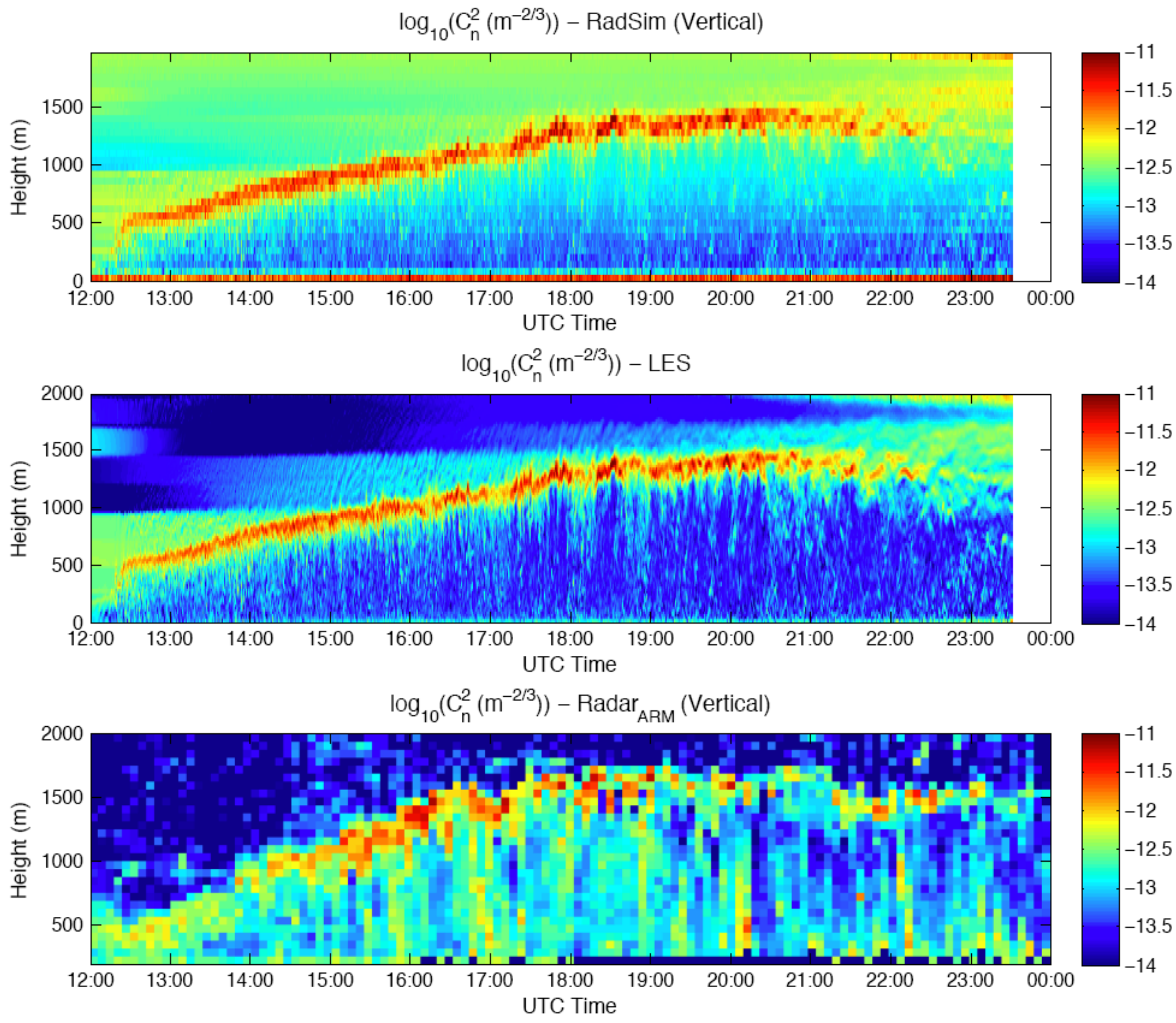
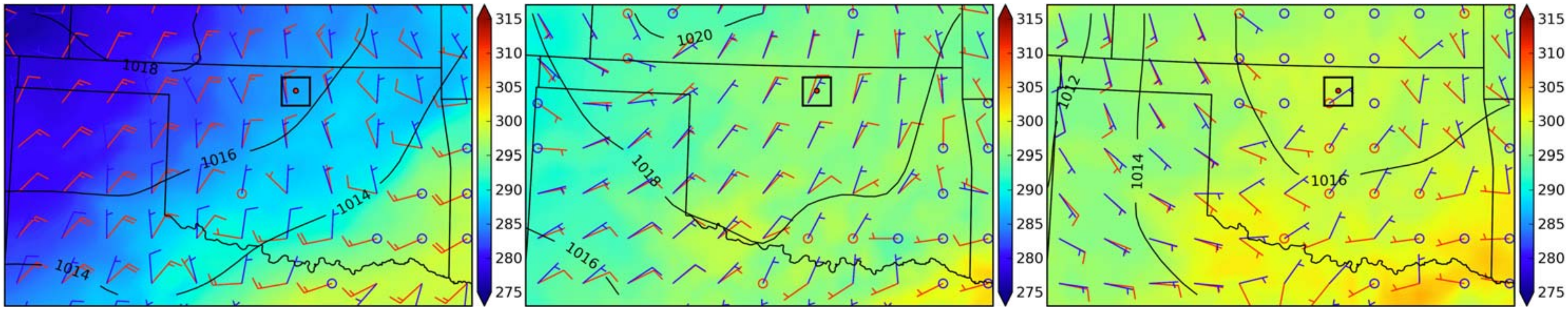
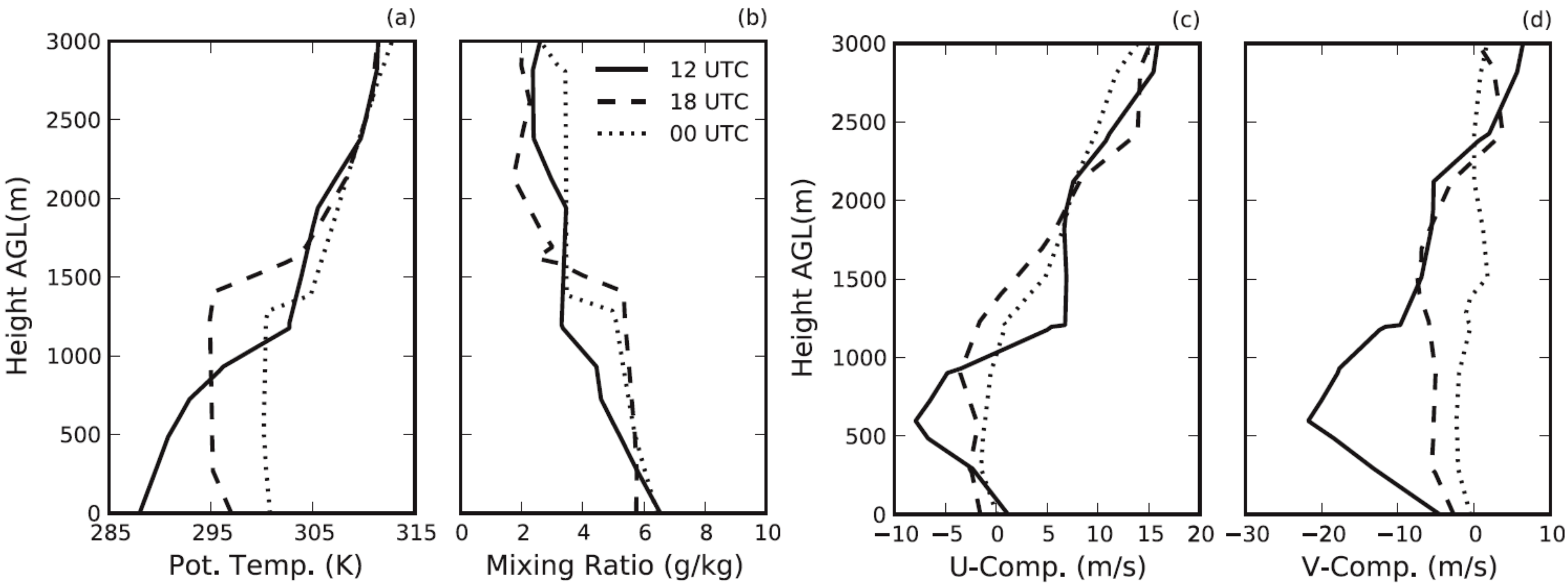



Figure 4.2: Structure function parameter of the refractive index estimates on June 8, 2007. Top: estimates from the vertical beam of the radar simulator. Middle: LES-profile at center of domain. Bottom: estimates from the vertical beam of the SGP ACRF radar.

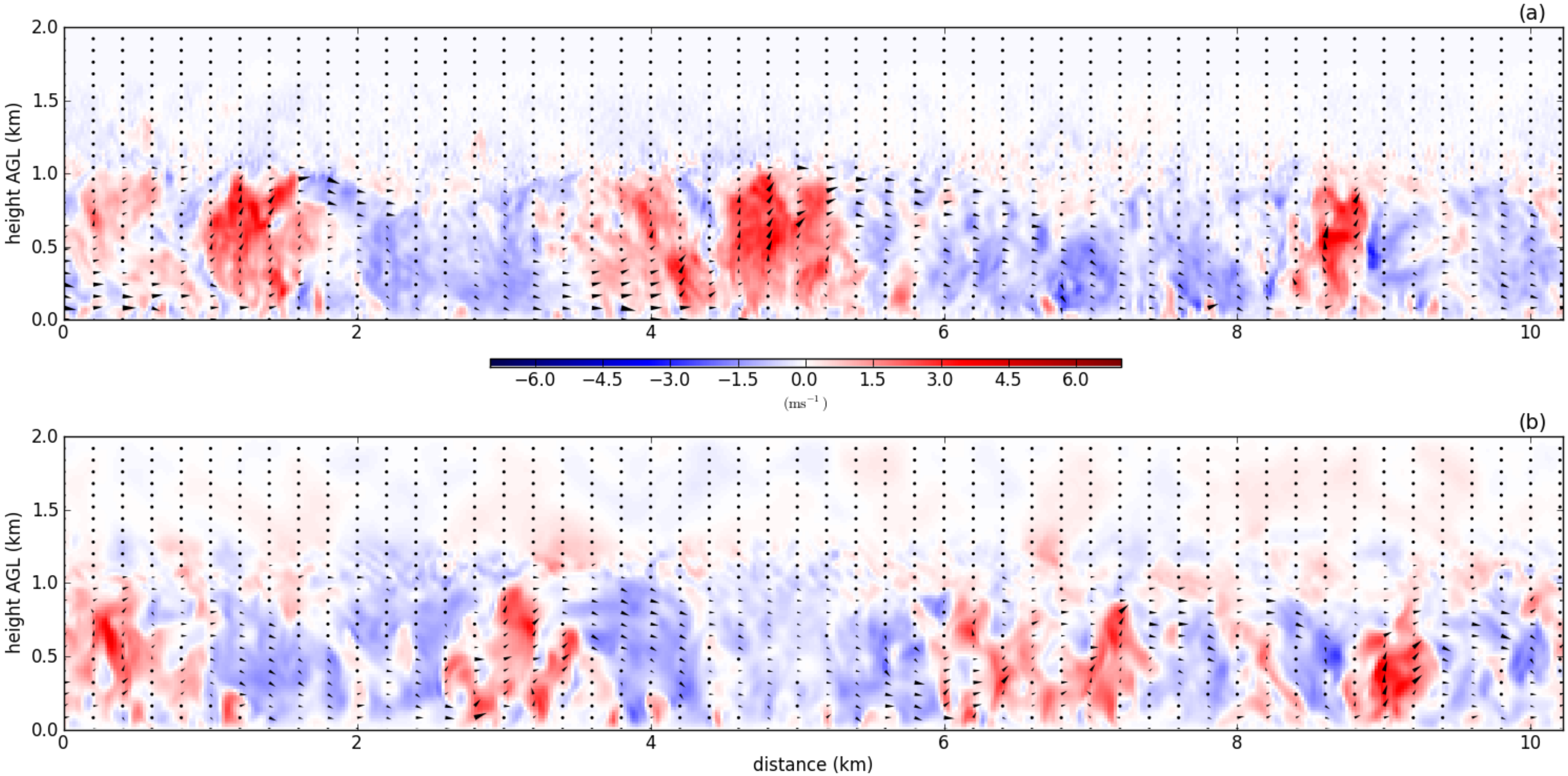
# CBL development in a cold-front environment




**12 UTC** 06/08/2007 **18 UTC** 06/08/2007 **00 UTC** 06/09/2007



# Structure of simulated idealized sheared CBL as viewed across horizontal convective rolls




## OU-LES (top), WRF-LES (bottom); *w* (+,-) field

**Thanks to Jeremy Gibbs (my Ph.D. student, OU)**