Parametrization of the planetary boundary layer (PBL)

Irina Sandu & Maike Ahlgrimm

Introduction	Irina
Surface layer and surface fluxes	Irina
Outer layer	Irina
PBL& Cloud evaluation	*Maike*
Exercises	*Irina & Maike*

Why studying the Planetary Boundary Layer ?

- Natural environment for human activities
- Understanding and predicting its structure
  - Agriculture, aeronautics, telecommunications, Earth energetic budget
- Weather forecast, pollutants dispersion, climate prediction





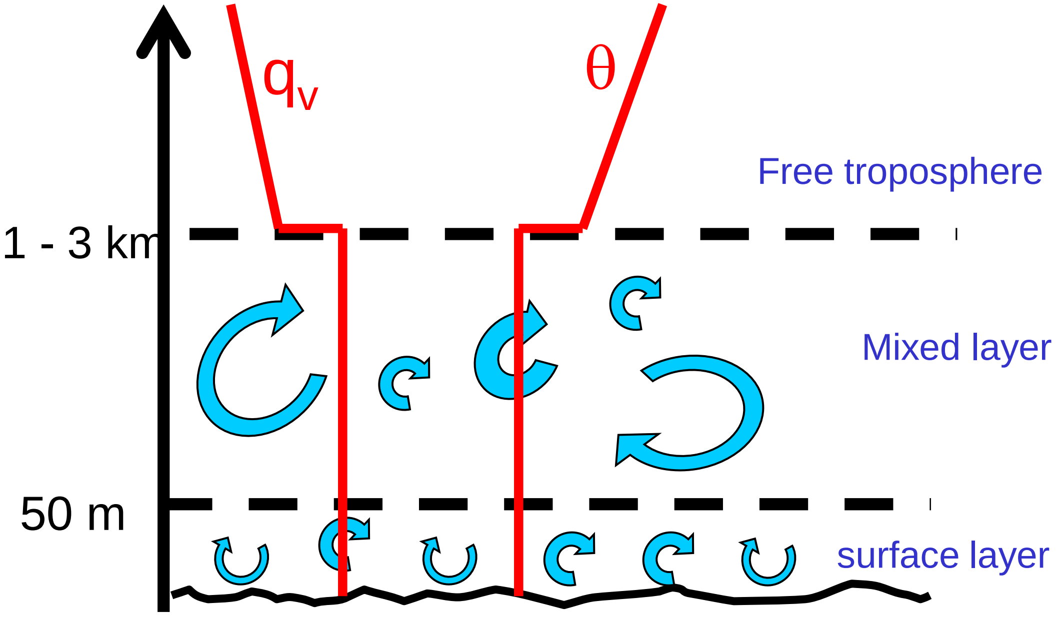
Outline

- ☞ Definition
- ☞ Turbulence/Equations
- ☞ Stability
- ☞ Classification
- ☞ Clear convective boundary layers
- ☞ Cloudy boundary layers (stratocumulus and cumulus)
- ☞ Summary

PBL: Definitions

The PBL is the layer close to the surface within which vertical transports by turbulence play dominant roles in the momentum, heat and moisture budgets.

- ☞ The layer where the flow is turbulent.
- ☞ The fluxes of momentum, heat or matter are carried by turbulent motions on a scale of the order of the depth of the boundary layer or less.
- ☞ The surface effects (friction, cooling, heating or moistening) are felt on times scales < 1 day.



Composition

- atmospheric gases (N_2, O_2, water vapor, …)
- aerosol particles
- clouds (condensed water)

PBL: Governing equations for the mean state

- ☞ gas law (equation of state)
- ☞ momentum (Navier Stokes)
- ☞ continuity eq. (conservation of mass)
- ☞ heat (first principle of thermodynamics)
- ☞ total water

Reynolds averaging $A = \overline{A} + A'$

Averaging (overbar) is over grid box, i.e. sub-grid turbulent motion is averaged out.

Simplifications

Boussinesq approximation (density fluctuations non-negligible only in buoyancy terms)

Hydrostatic approximation (balance of pressure gradient and gravity forces)

Incompressibility approximation (changes in density are negligible)

PBL: Governing equations for the mean state

Reynolds averaging $A = \overline{A} + A'$

Need to be parameterized !

☞ gas law $\bar{p} = \bar{\rho}\, R_d \overline{T_v}$ $\overline{T_v} = T(1 + 0.61 q_v - q_l)$

virtual temperature

2nd order

☞ momentum

$$\frac{\partial \overline{u_i}}{\partial t} + \overline{u_j}\frac{\partial \overline{u_i}}{\partial x_j} = -\delta_{i3} g + f_c \varepsilon_{ij3} \overline{u_j} - \frac{1}{\overline{\rho}}\frac{\partial \overline{P}}{\partial x_i} + \frac{\upsilon \partial^2 \overline{u_i}}{\partial x_j{}^2} - \frac{\partial(\overline{u'_i u'_j})}{\partial x_j}$$

mean advection | gravity | Coriolis | Pressure gradient | Viscous stress | Turbulent transport

☞ continuity eq. $\frac{\partial \overline{u_i}}{\partial x_j} = 0$

☞ heat

$$\frac{\partial \overline{\theta}}{\partial t} + \overline{u_j}\frac{\partial \overline{\theta}}{\partial x_j} = -\frac{1}{\overline{\rho} c_p}\frac{\partial \overline{F_j}}{\partial x_j} - \frac{\partial \overline{u'_j \theta'}}{\partial x_j} - \frac{L_v E}{\overline{\rho} c_p}$$

mean advection | radiation | turbulent transport | Latent heat release

☞ total water

$$\frac{\partial \overline{q_t}}{\partial t} + \overline{u_j}\frac{\partial \overline{q_t}}{\partial x_j} = \frac{S_{q_t}}{\overline{\rho}} - \frac{\partial \overline{u'_j q'_t}}{\partial x_j}$$

mean advection | precipitation | turbulent transport

PBL: Turbulent kinetic energy equation

☞ TKE: a measure of the intensity of turbulent mixing $\bar{e} = \frac{1}{2}(\overline{u'^2} + \overline{v'^2} + \overline{w'^2})$

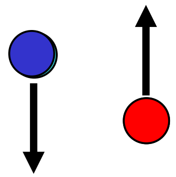
$$\frac{\partial \bar{e}}{\partial t} + \overline{u_j}\frac{\partial \bar{e}}{\partial x_j} = \frac{g}{\theta_0}\overline{w'\theta_v'} - \overline{u_i' u_j'}\frac{\partial \overline{u_i}}{\partial x_j} - \frac{\partial \overline{u_j' e}}{\partial x_j} - \frac{1}{\rho}\frac{\partial \overline{u_i' p'}}{\partial x_i} - \varepsilon$$

buoyancy production | mechanical shear | turbulent transport | pressure transport | dissipation

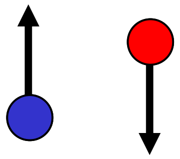
$$\theta_v = \theta\left(1 + 0.61 q_v - q_l\right)$$ virtual potential temperature

☞ An example：

✘ $\theta_v' < 0$, $w' < 0$ or $\theta_v' > 0$, $w' > 0$ ⟶ $w'\theta_v' > 0$ source



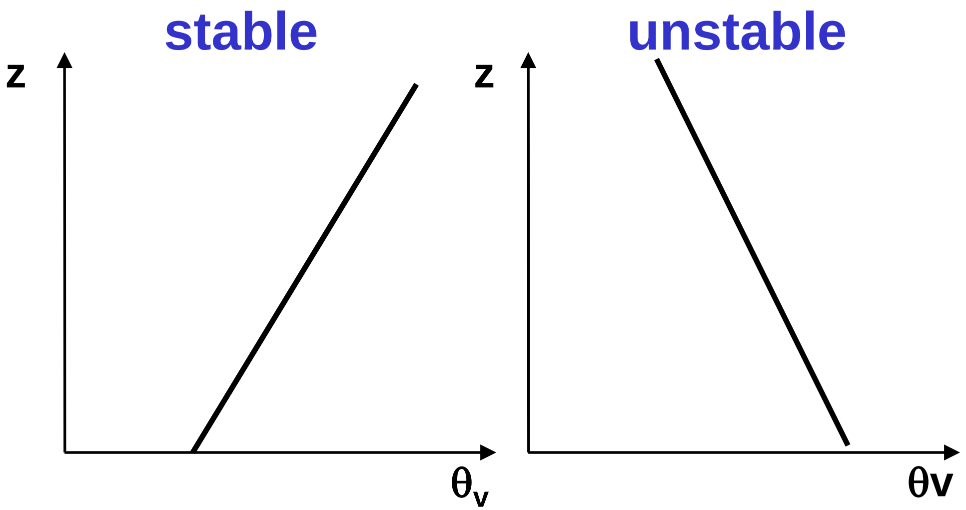
✘ $\theta_v' < 0$, $w' > 0$ or $\theta_v' > 0$, $w' < 0$ ⟶ $w'\theta_v' < 0$ sink



PBL: Stability (I)

- Traditionally stability is defined using the temperature gradient

- θ_v gradient (local definition):
  - $\dfrac{\partial \overline{\theta_v}}{\partial z} > 0$ stable layer
  - $\dfrac{\partial \overline{\theta_v}}{\partial z} < 0$ unstable layer
  - $\dfrac{\partial \overline{\theta_v}}{\partial z} = 0$ neutral layer



- How to determine the stability of the PBL taken as a whole ?
  - In a mixed layer the gradient of temperature is practically zero
  - Either θ_v or $w'\theta_v'$ profiles are needed to determine the PBL stability state

PBL: Other ways to determine stability (II)

Bouyancy flux at the surface:

$\overline{w'\theta_v'} > 0$ unstable PBL (convective)

$\overline{w'\theta_v'} < 0$ stable PBL

$\overline{w'\theta_v'} = 0$ neutral PBL

Or dynamic production of TKE integrated over the PBL depth stronger than thermal production

Monin-Obukhov length:

$$L = \frac{-\overline{\theta_v} u_*^3}{kg(\overline{w'\theta_v'})_s}, \quad u_*^2 = (\overline{u'w'})_s$$

$-10^5\text{m} \le L \le -100\text{m}$	unstable PBL
$-100\text{m} < L < 0$	strongly unstable PBL
$0 < L < 10$	strongly stable PBL
$10\text{m} \le L \le 10^5\text{m}$	stable PBL
$\|L\| > 10^5\text{m}$	neutral PBL

PBL: Classification and scaling

Neutral PBL :

- turbulence scale l ~ 0.07 H, H being the PBL depth
- Quasi-isotropic turbulence
- Scaling - adimensional parameters : z_0, H, u_*

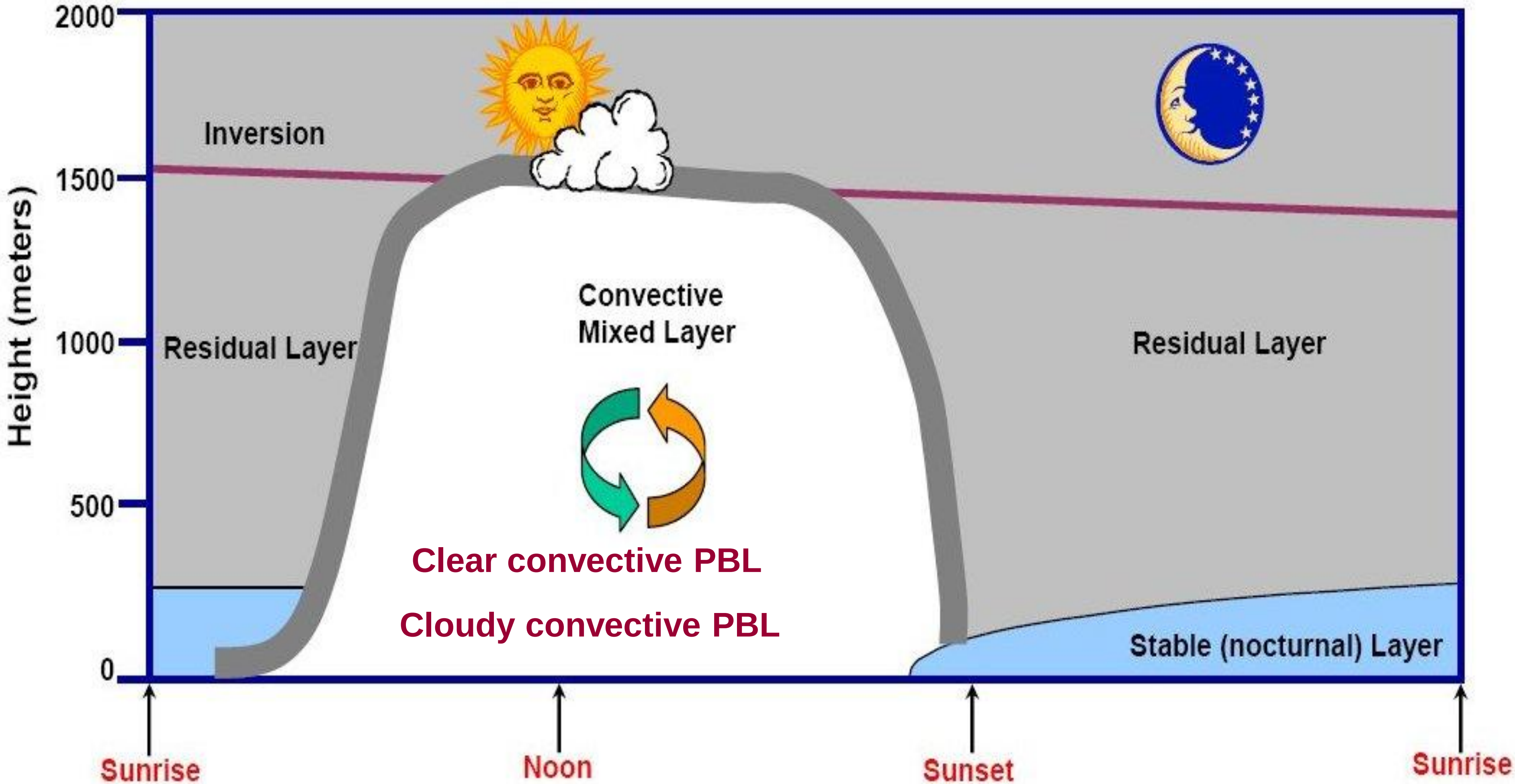
Stable PBL:

- l << H (stability embeds turbulent motion)
- Turbulence is local (no influence from surface), stronger on horizontal
- Scaling : $(\overline{w'\theta'})_s$, $(\overline{u'w'})_s$, H

Unstable (convective) PBL

- l ~ H (large eddies)
- Turbulence associated mostly to thermal production
- Turbulence is non-homogeneous and asymmetric (top-down, bottom-up)
- Scaling: H, $w_* = \left(\frac{g}{\overline{\theta}_v} (\overline{w'\theta'_v})_s H \right)^{1/3} \longrightarrow \frac{z}{H}, q_* = \frac{E_0}{w_*}, \theta_* = \frac{Q_0}{w_*}$

PBL: Diurnal variation



Adapted from **Introduction to Boundary Layer Meteorology** -R.B. Stull, 1988

PBL: State variables

Clear PBL

Specific humidity $$q_v = \frac{m_v}{m_d + m_v}$$

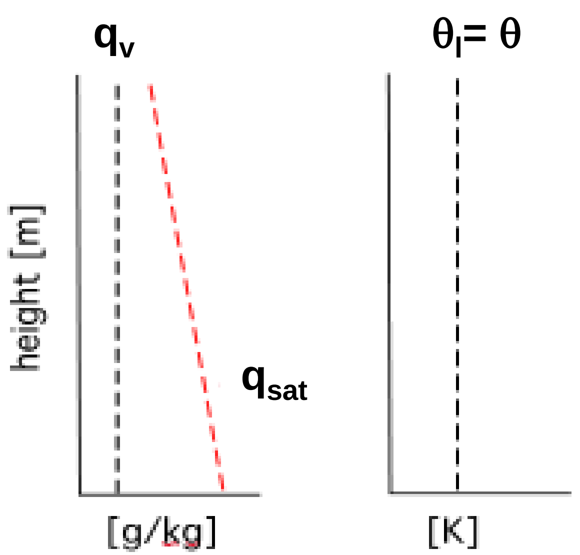
Potential temperature $$\theta = T\left(\frac{p}{p_0}\right)^{-R_d/c_p}$$

Cloudy PBL

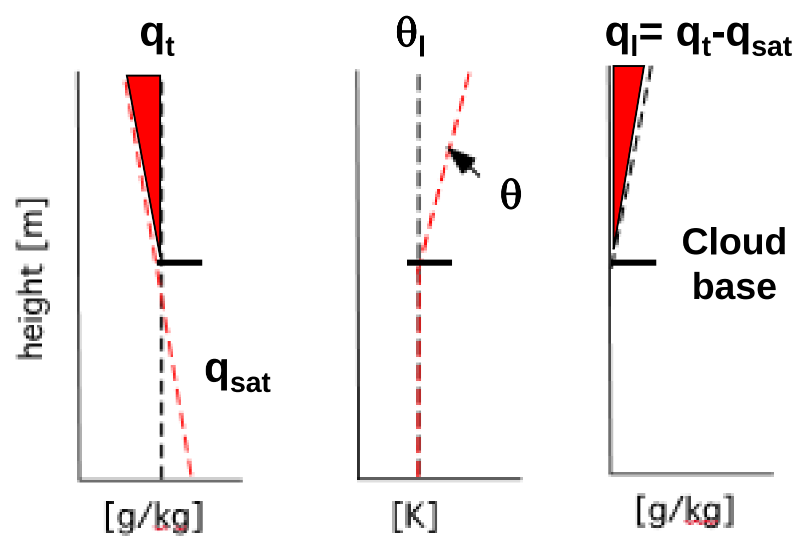
Total water content $$q_t = \frac{m_v + m_c}{m_d + m_v + m_c}$$

Liquid water potential temperature $$\theta_l \approx \theta - \frac{L_v}{c_p} q_l$$ Evaporation temperature

no liquid water is condensed ($q_l = 0$)



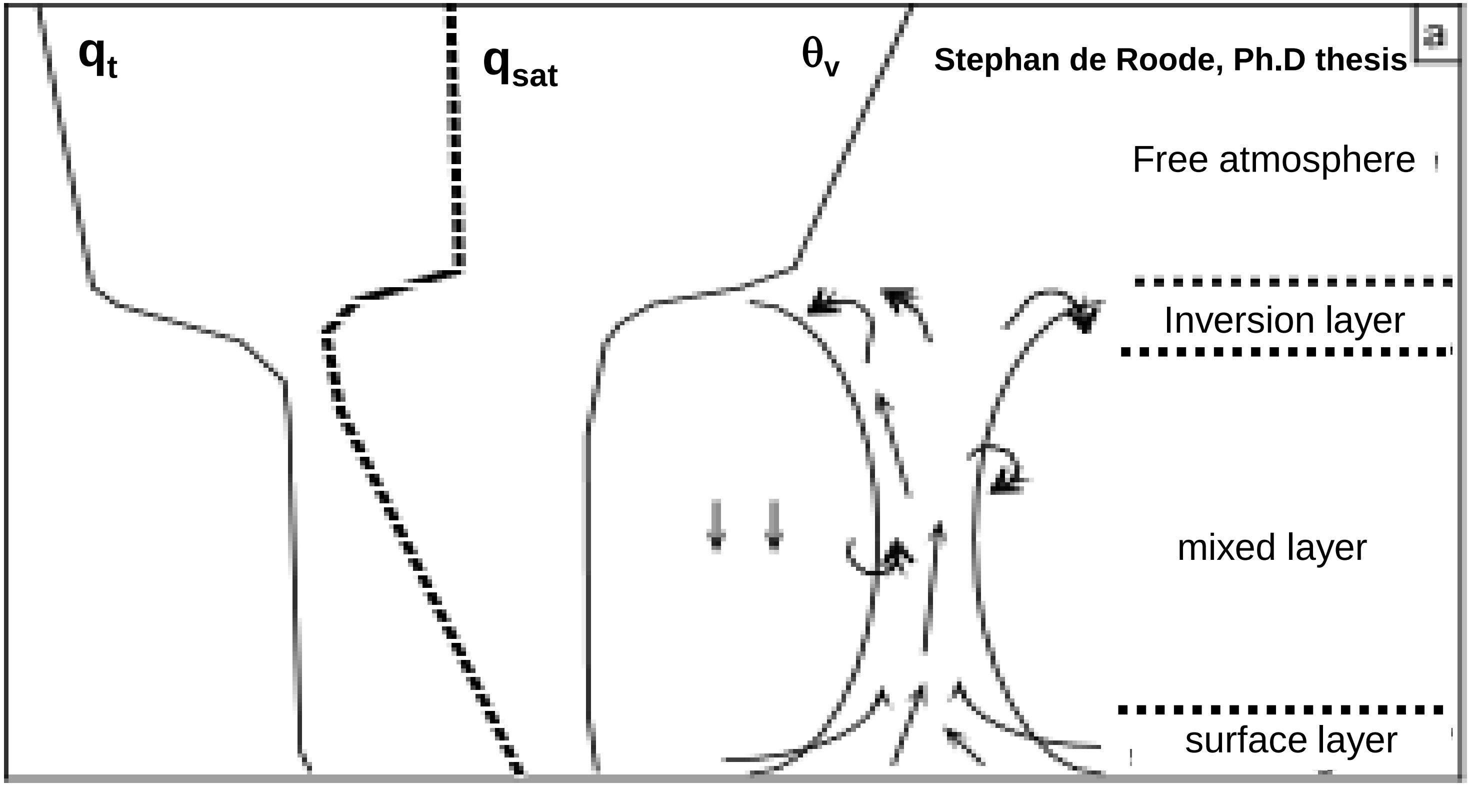
liquid water is condensed



Conserved variables

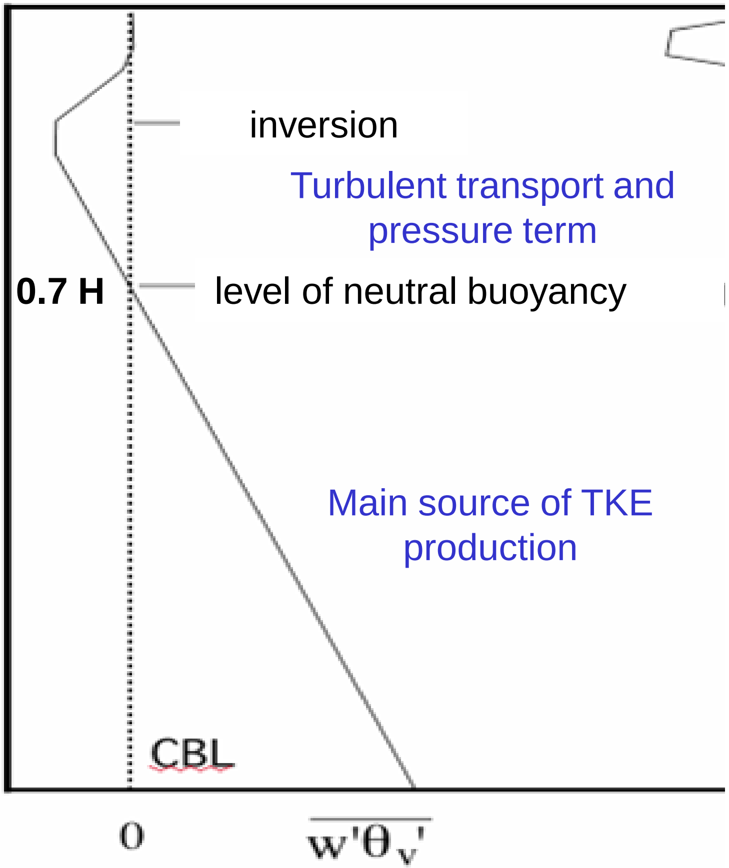
Conserved variables

Clear Convective PBL



Clear Convective PBL

☞ Buoyantly-driven from surface



☞ PBL height: $\frac{dH}{dt} = \overline{w} + w_e$

☞ Entrainment rate: $w_e = A \frac{w_*^3}{\frac{g}{\theta_0} H \Delta\theta_v}$ with
(a possible parameterization)

$$w_* = \left(\frac{g}{\theta_v} (\overline{w'\theta_v'})_s H \right)^{1/3}$$

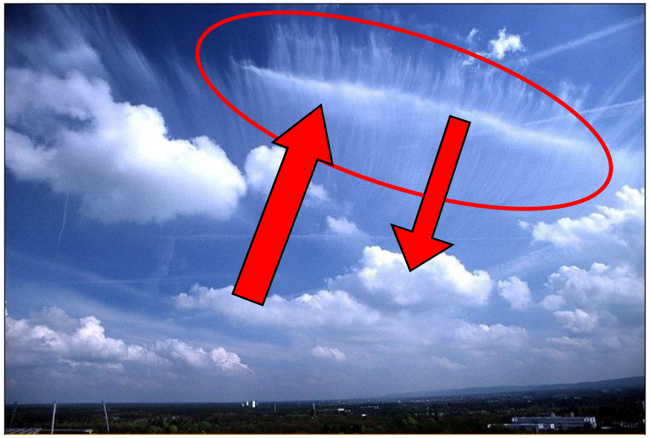
☞ Fluxes at PBL top: $\overline{w'\psi_H'} = -w_e \Delta\psi$

☞ Key parameters: $w_e, \Delta\theta_v, H, \overline{(w'\theta_v')_0}$

Clouds effects on climate

Greenhouse effect : warming

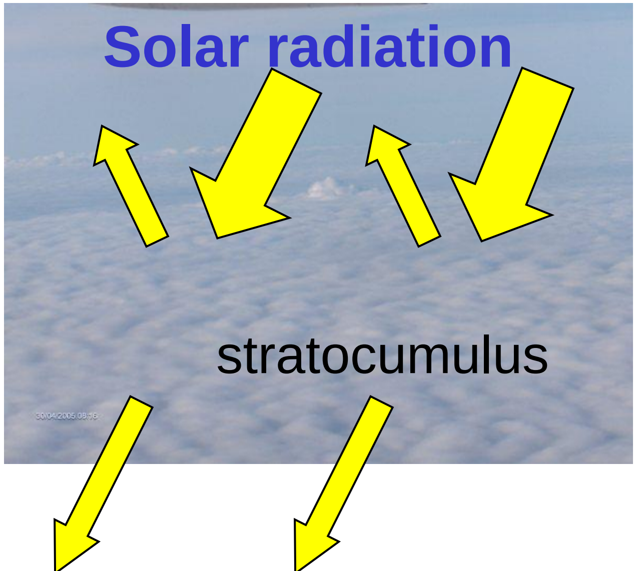
High clouds, like cirrus



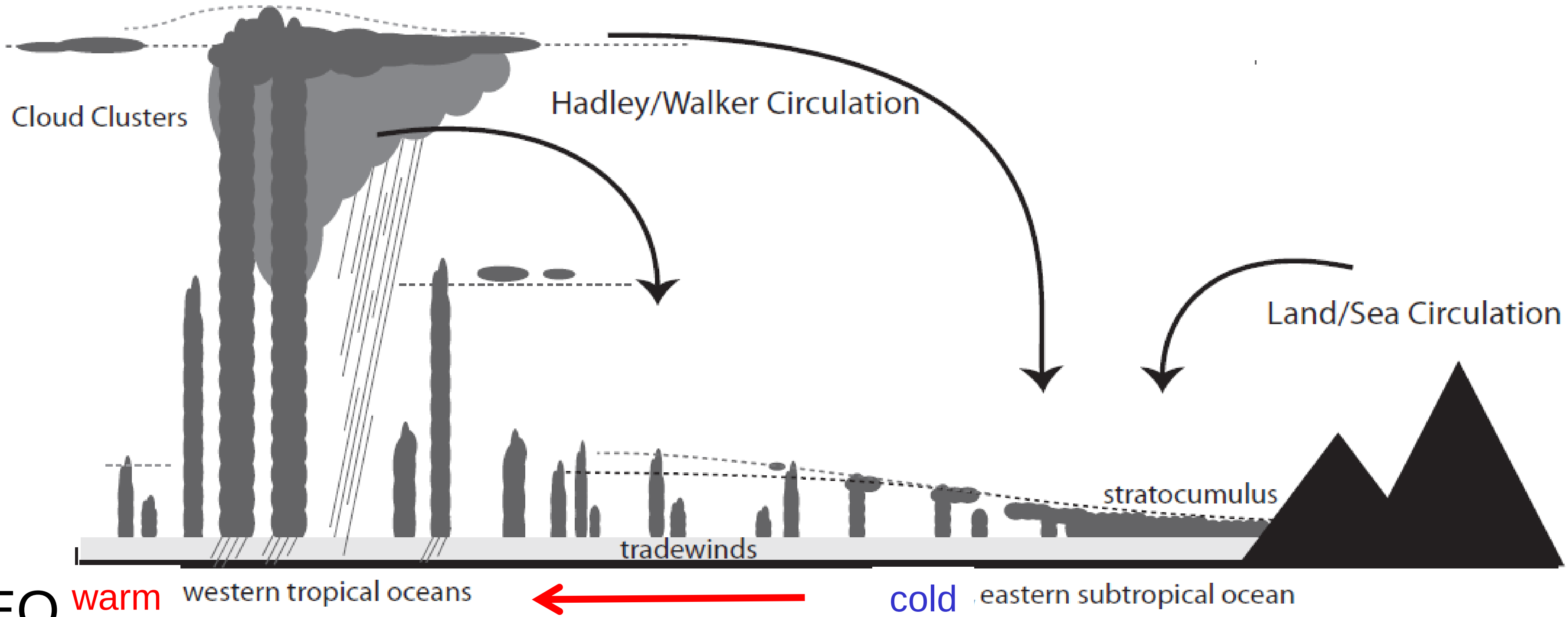
Infrared radiation

Umbrella effect : cooling

Boundary layer clouds (low clouds)

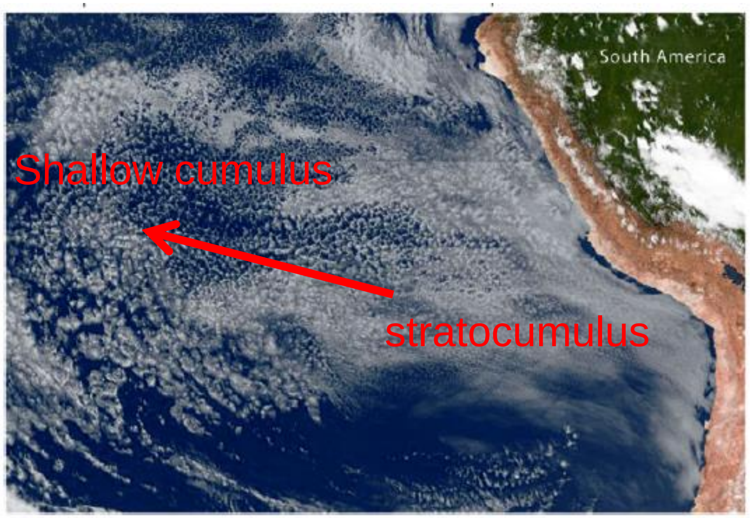


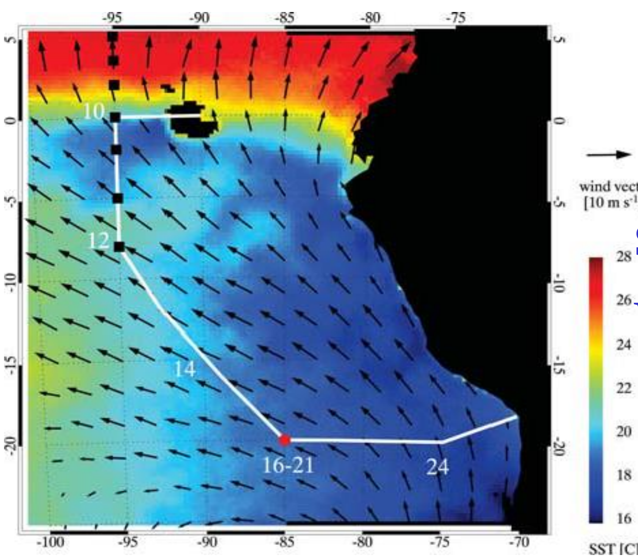
Boundary layer clouds over oceans



EQ warm

cold

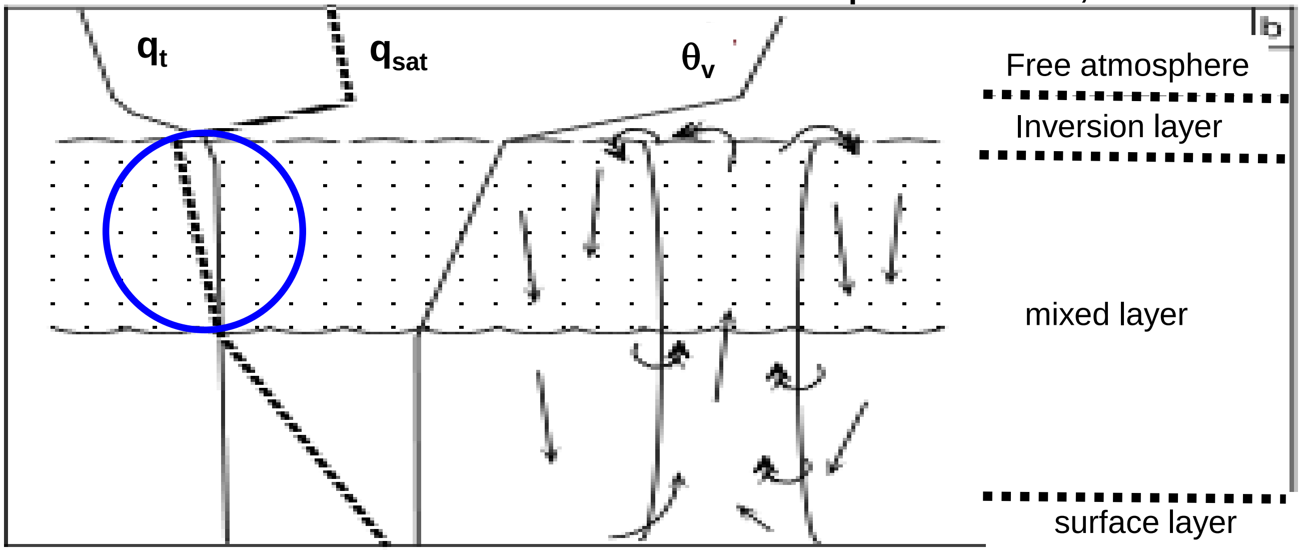




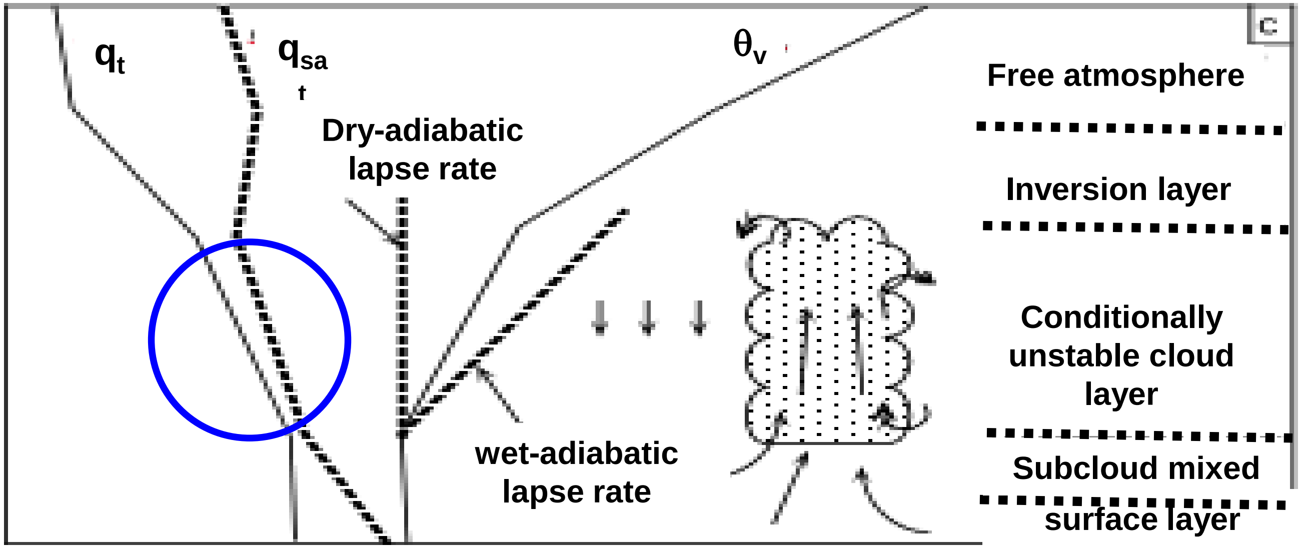
SST & surface wind

Cloudy boundary layers

Stephan de Roode, Ph.D thesis



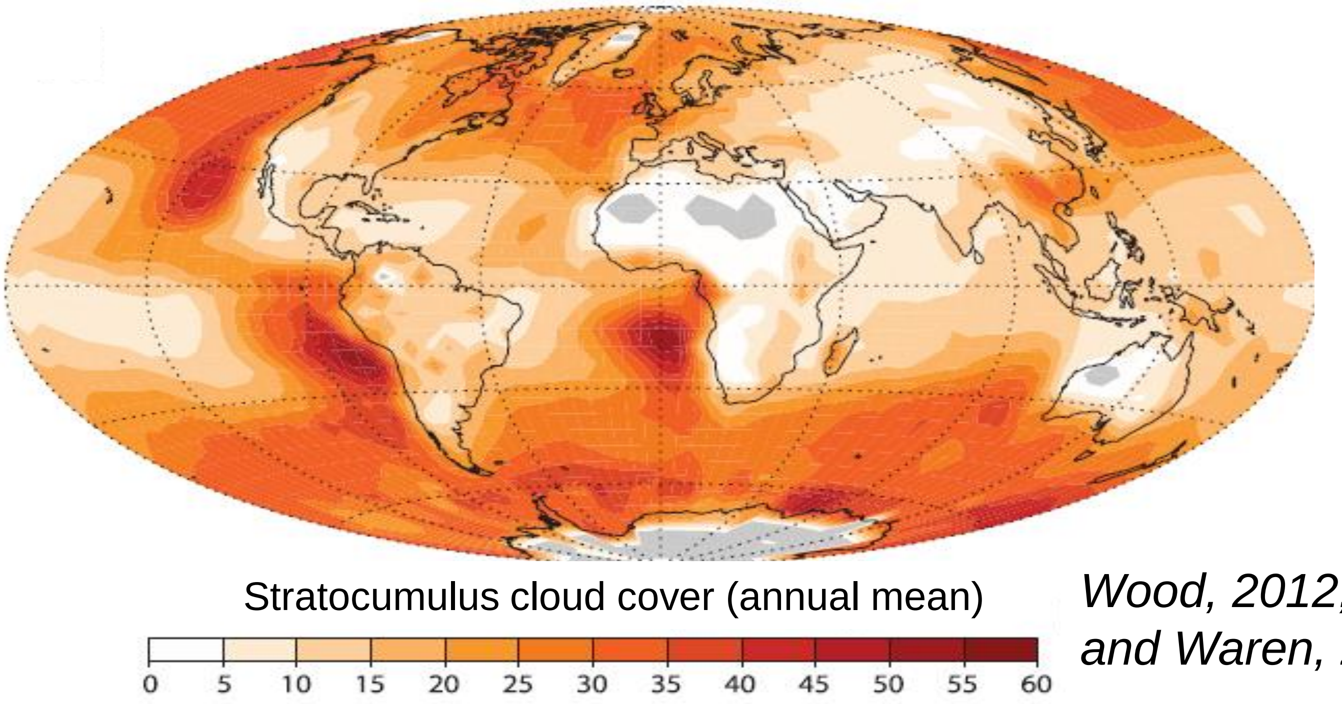
Stratocumulus topped PBL



Cumulus PBL

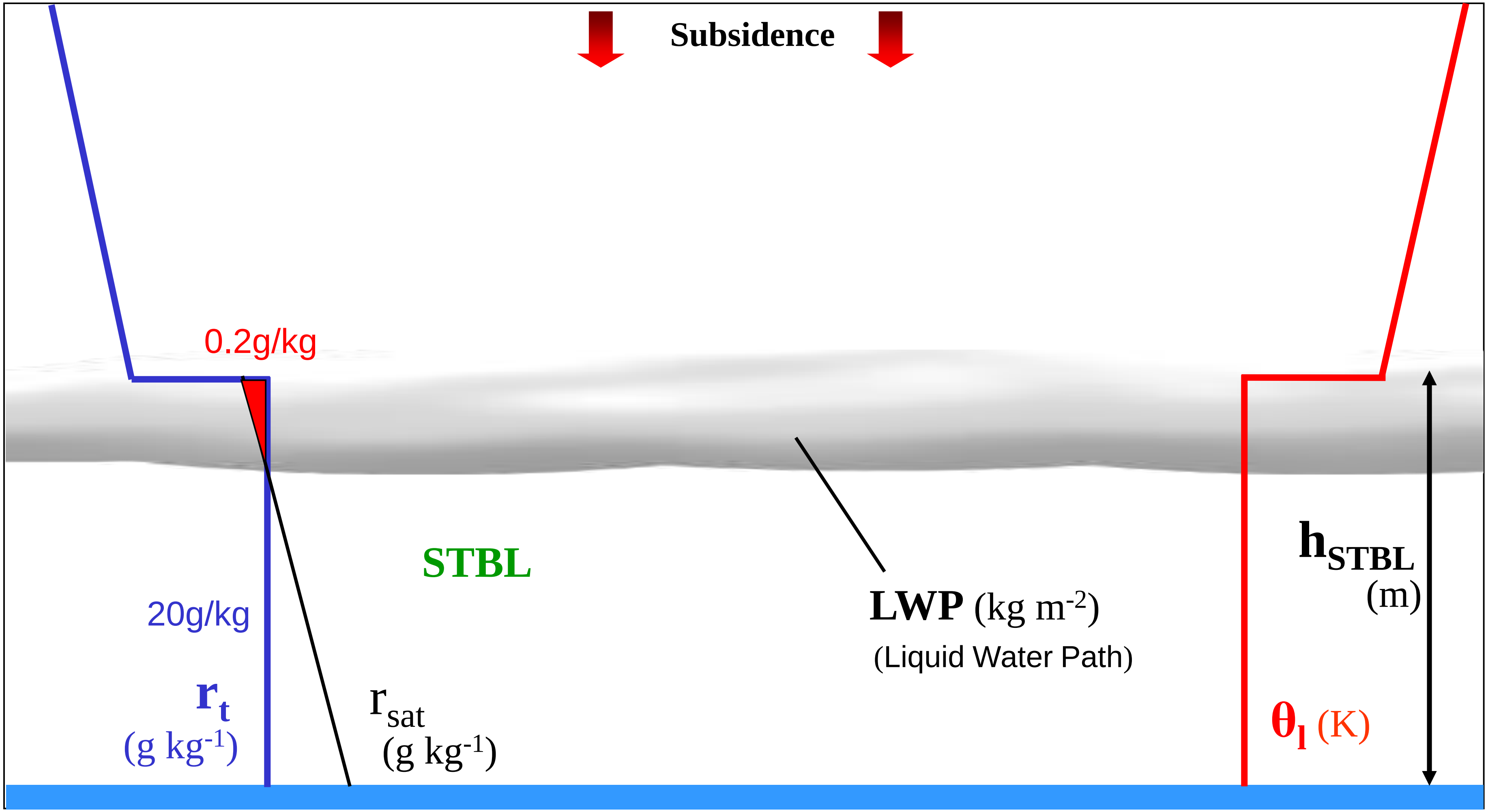
Stratocumulus – Why are they important?

- ☞ Cover in (annual) mean 29% of the planet (Klein and Hartmann, 1993)
- ☞ Cloud top albedo is 50-80% (in contrast to 7 % at ocean surface).
- ☞ A 4% increase in global stratocumulus extend would offset 2-3K global warming from CO_2 doubling (Randall et al. 1984).
- ☞ Coupled models have large biases in stratocumulus extent and SSTs.

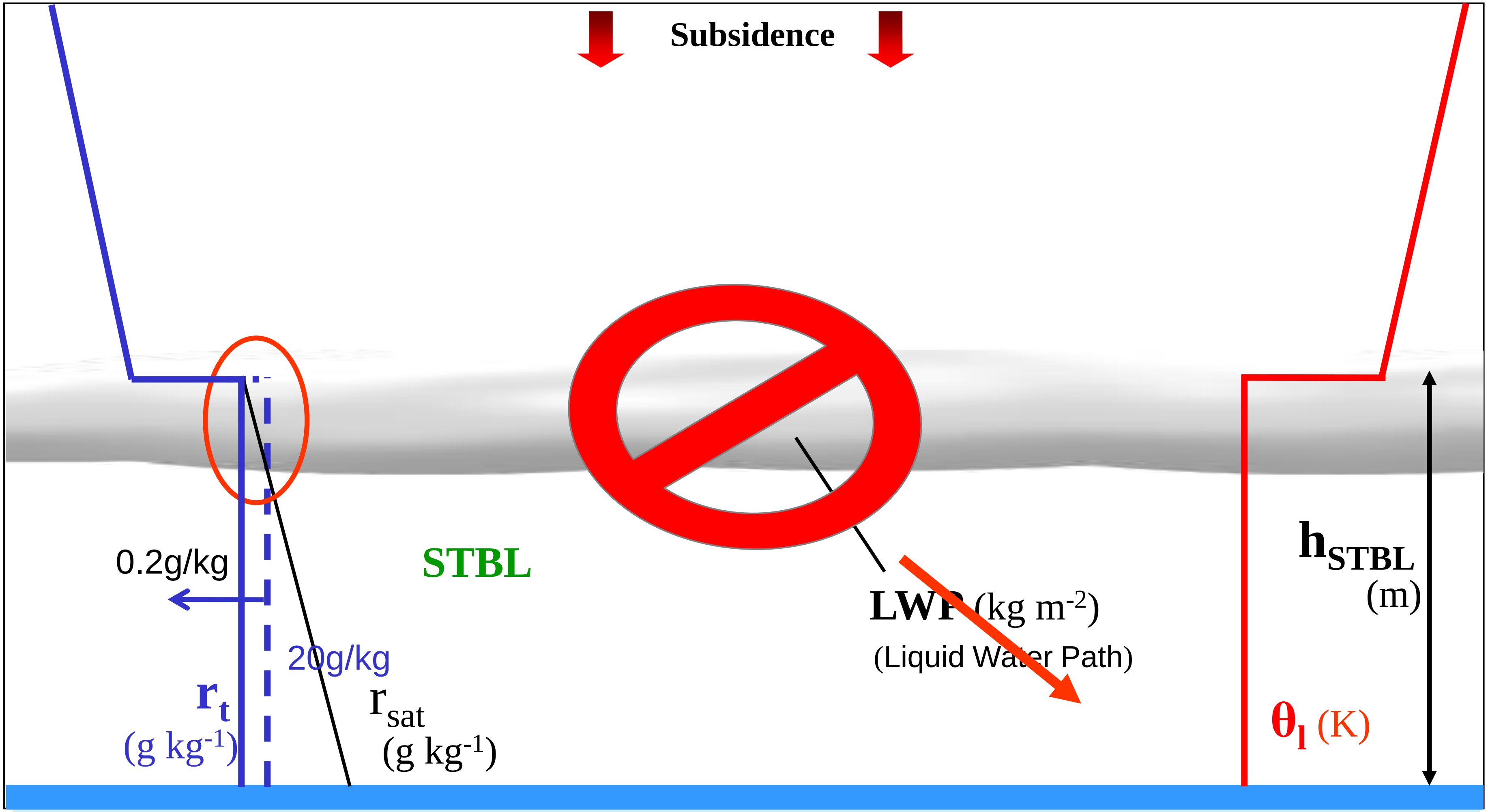


Wood, 2012,based on Han and Waren, 2007

Characterisation of a stratocumulus topped PBL

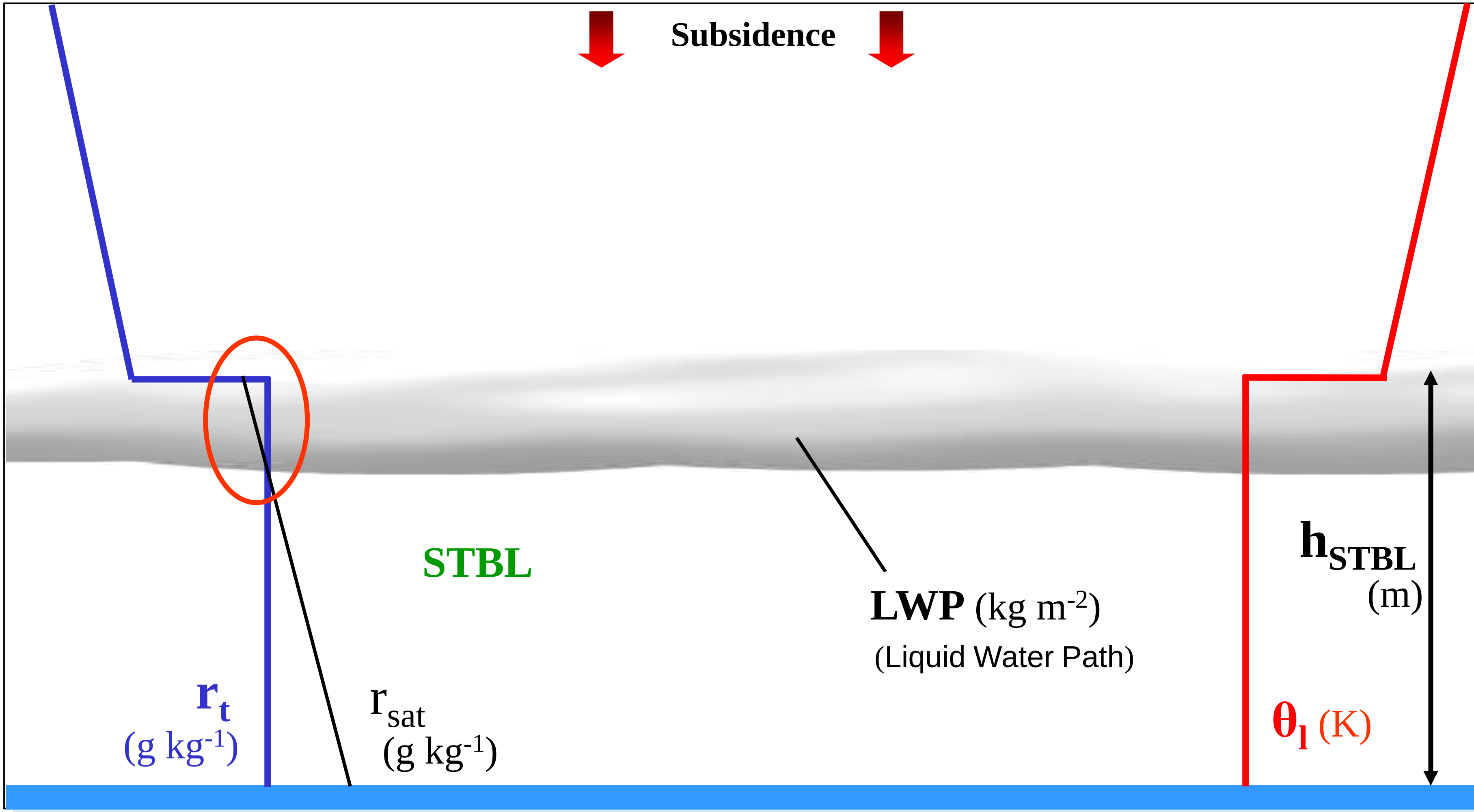


Characterisation of a stratocumulus topped PBL



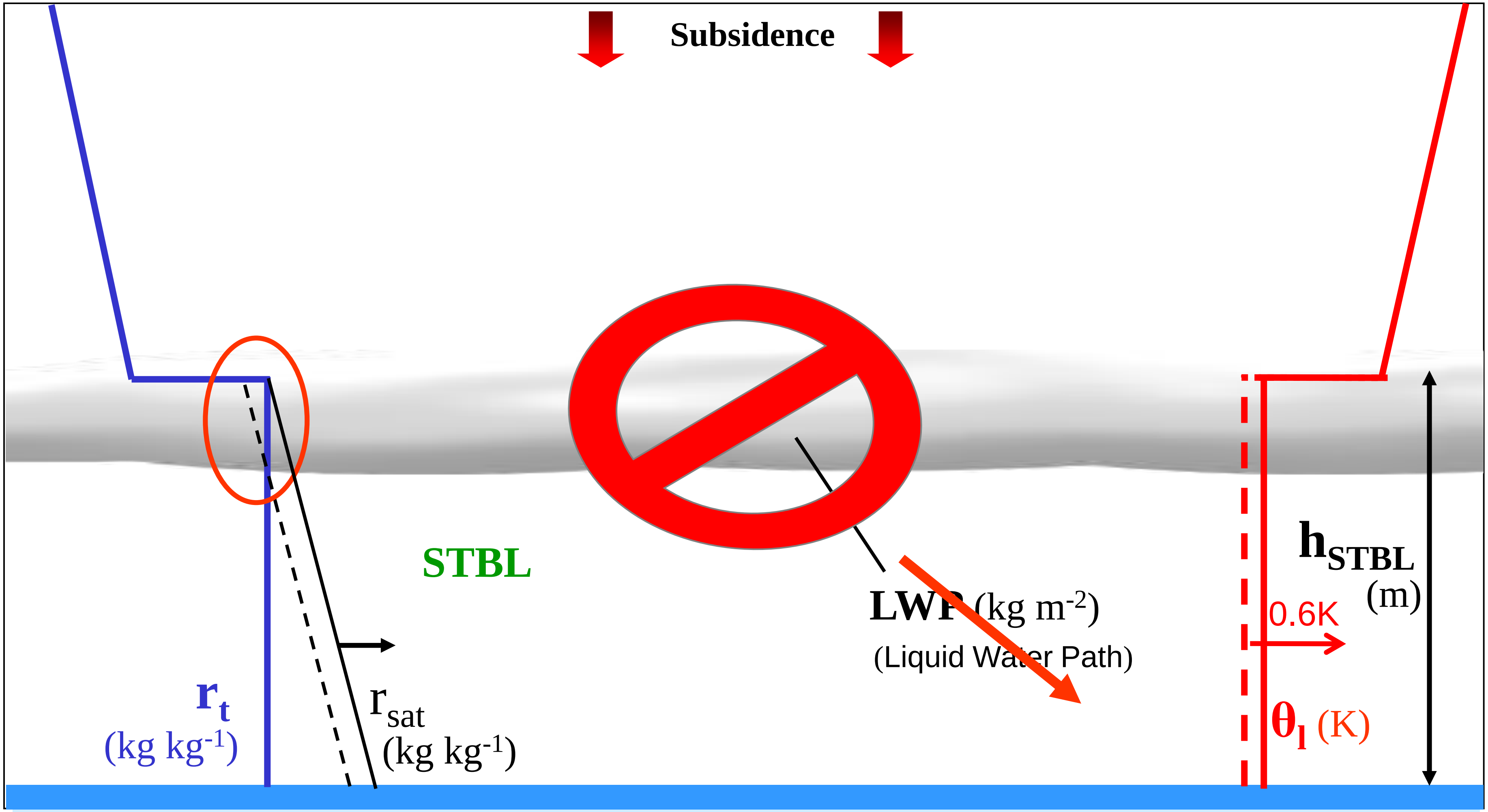
Such a cloudy system is extremely sensitive to thermodynamical conditions

Characterisation of a stratocumulus topped PBL



Such a cloudy system is extremely sensitive to thermodynamical conditions

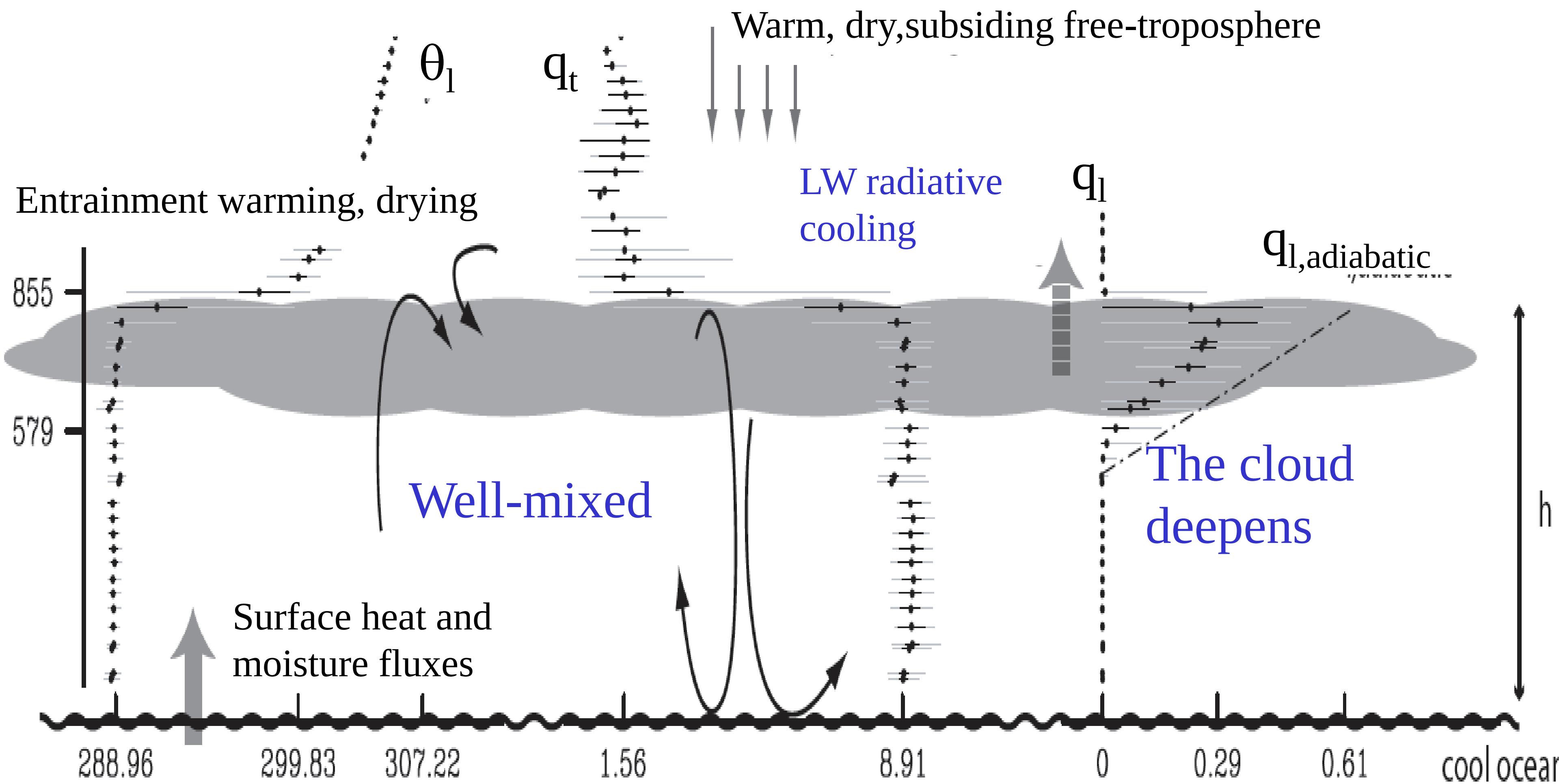
Characterisation of a stratocumulus topped PBL



Such a cloudy system is extremely sensitive to thermodynamical conditions

Processes controlling the evolution of a non-precipitating stratocumulus

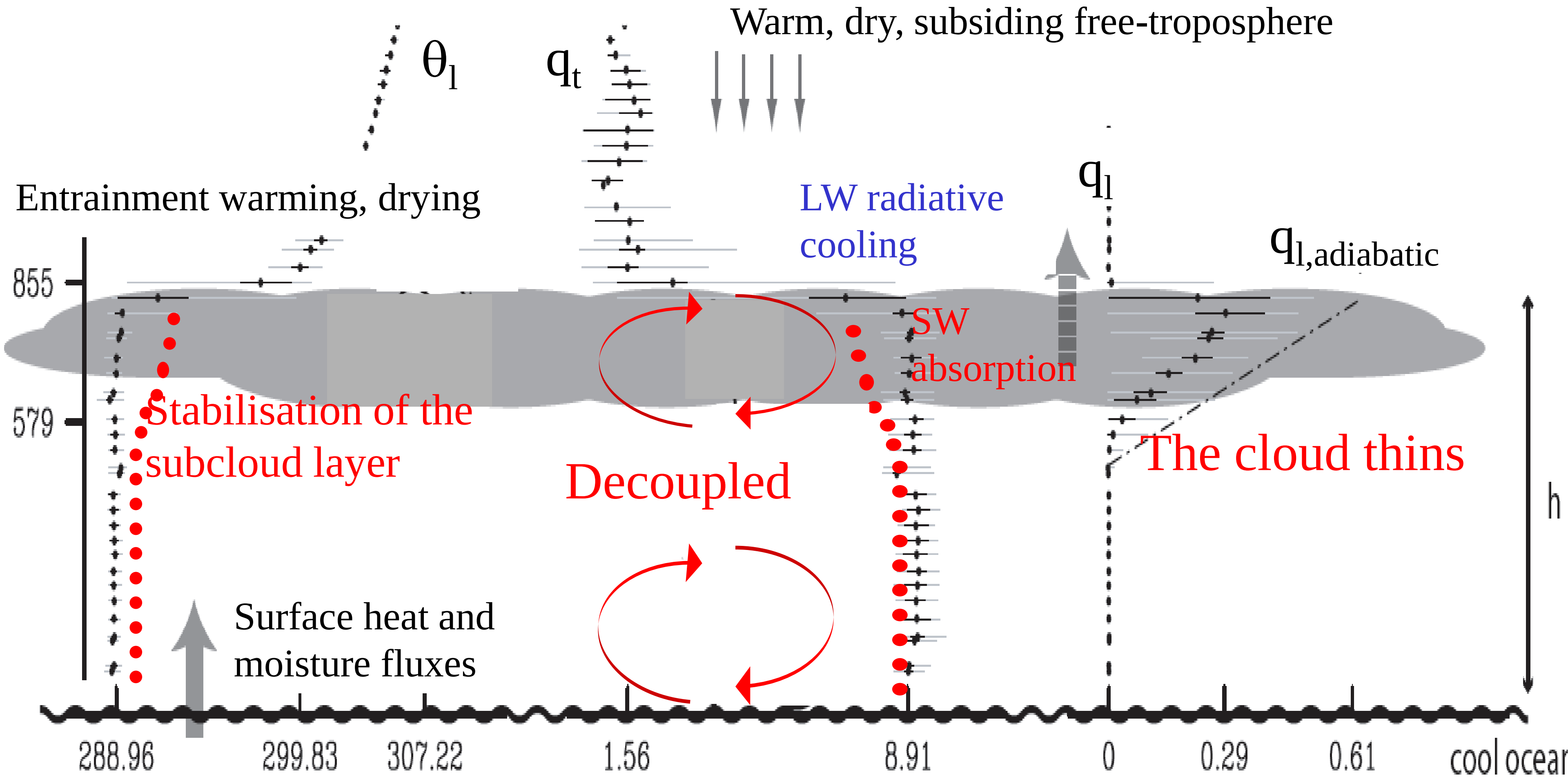
Night-time



Courtesy of Bjorn Stevens (data from DYCOMS-II)

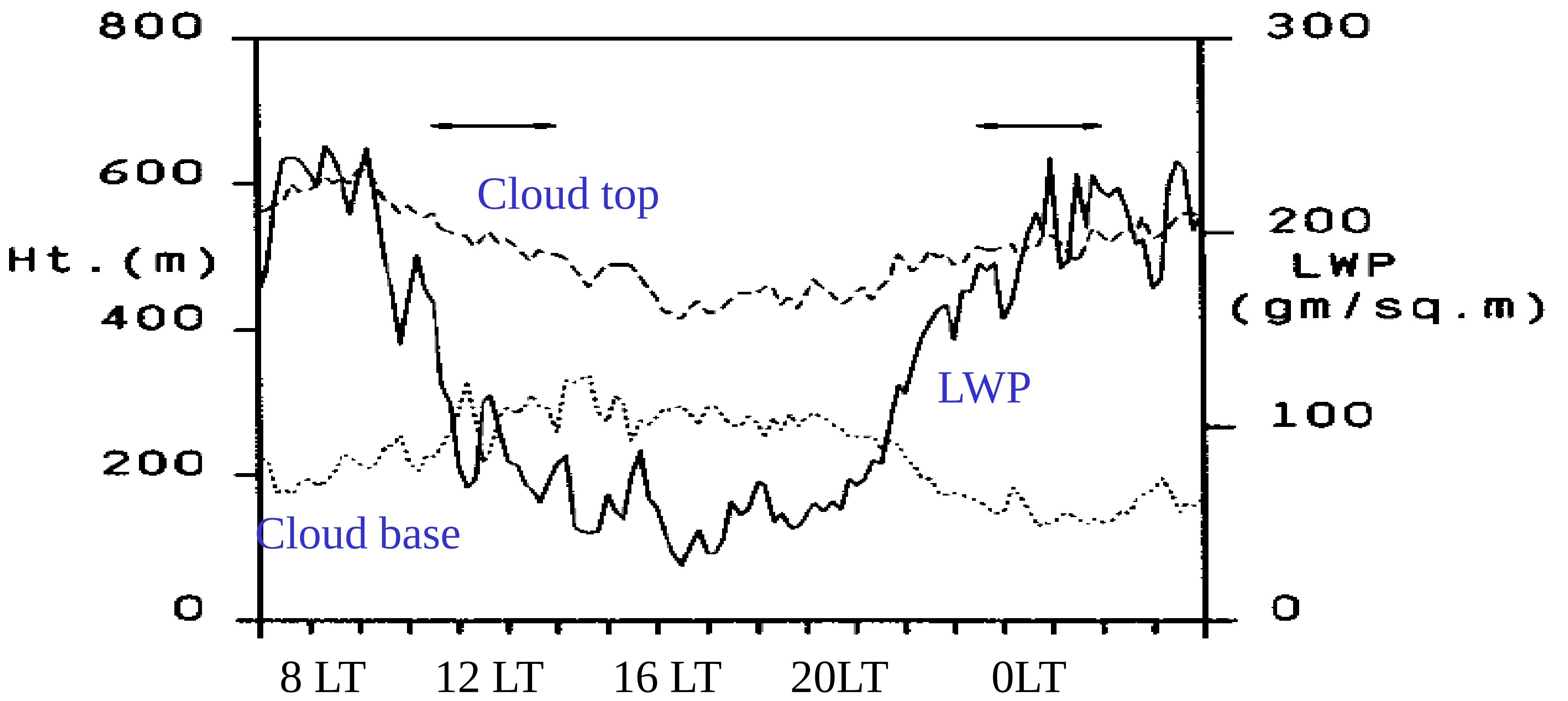
Processes controlling the evolution of a non-precipitating stratocumulus

Daytime



Courtesy of Bjorn Stevens (data from DYCOMS-II)

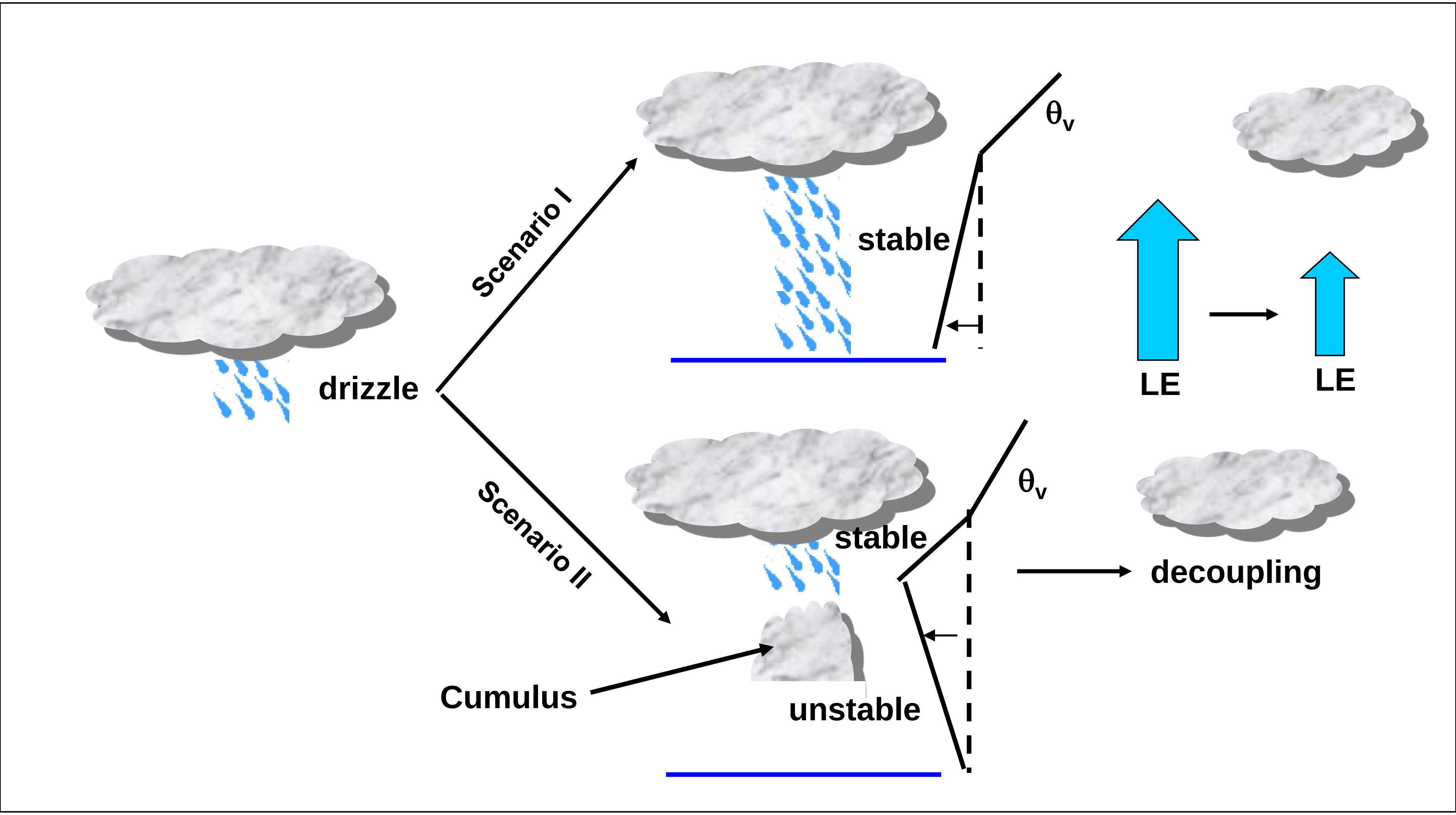
Diurnal cycle during observed during FIRE-I experiment



Hignett, 1991 (data from FIRE-I)

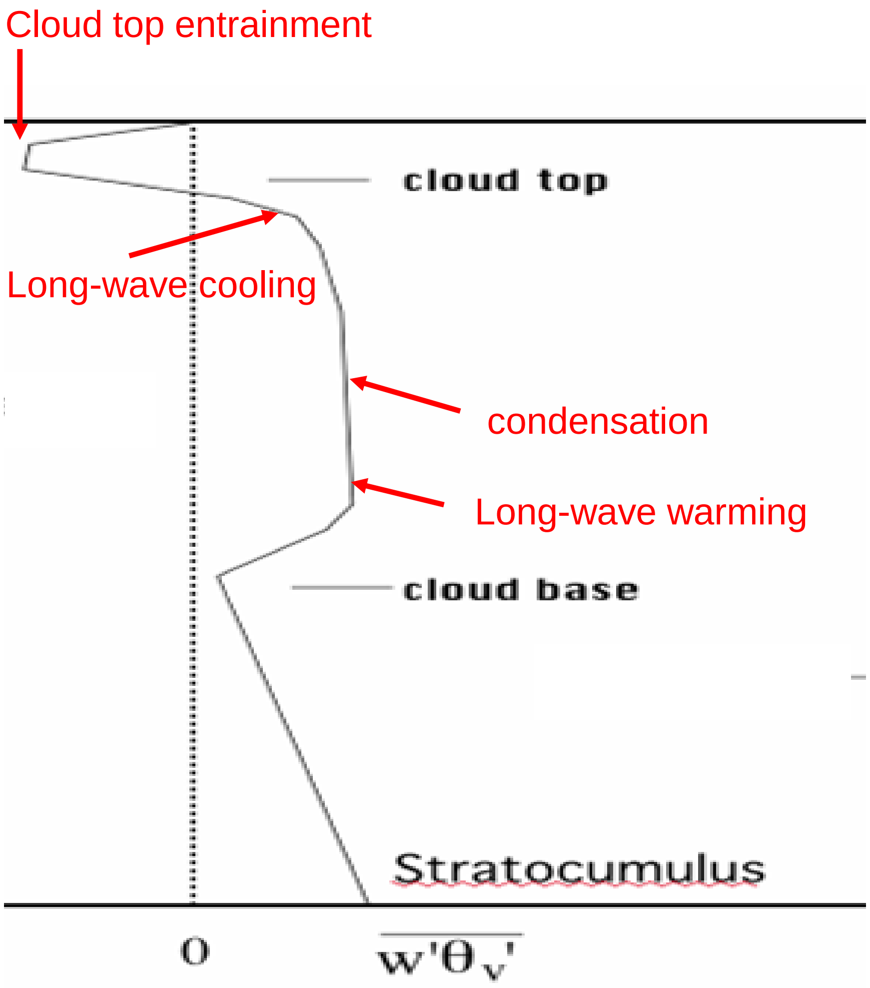
Precipitation flux

☞ Under cloud evaporation affects the dynamics of the boundary layer



Stratocumulus topped boundary layer

☞ Complicated turbulence structure



☞ Buoyantly driven by radiative cooling at cloud top

☞ Surface latent and heat flux play an important role

☞ Cloud top entrainment an order of magnitude stronger than in clear PBL

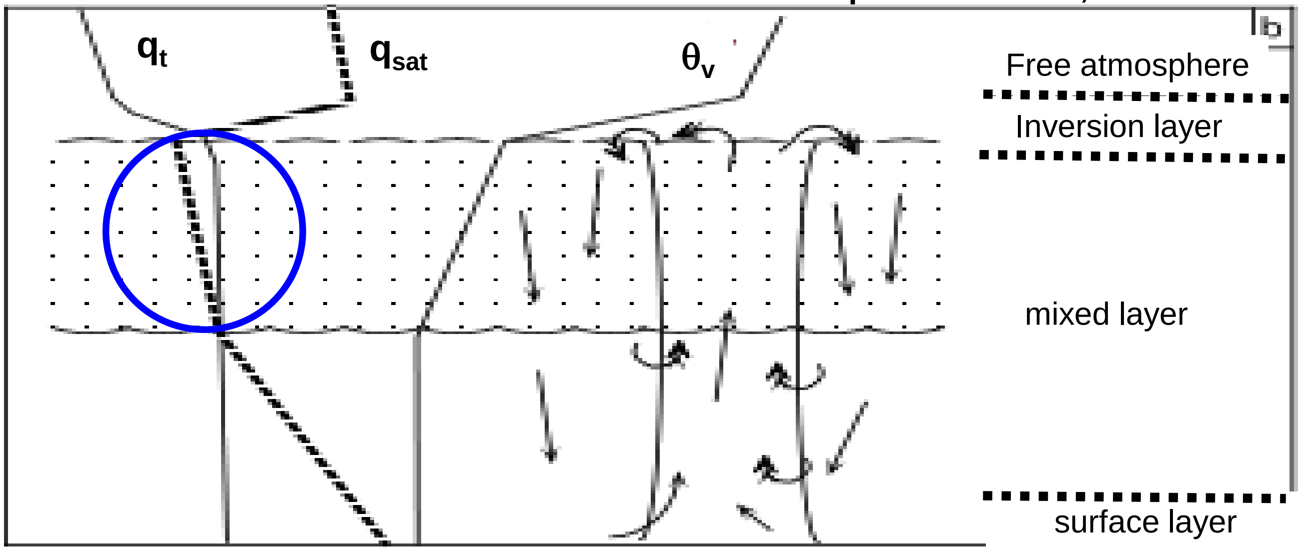
☞ Solar radiation transfer essential for the cloud evolution

☞ Key parameters: $w_e, \Delta\theta_v, H, \overline{(w'\theta_v')_0}$

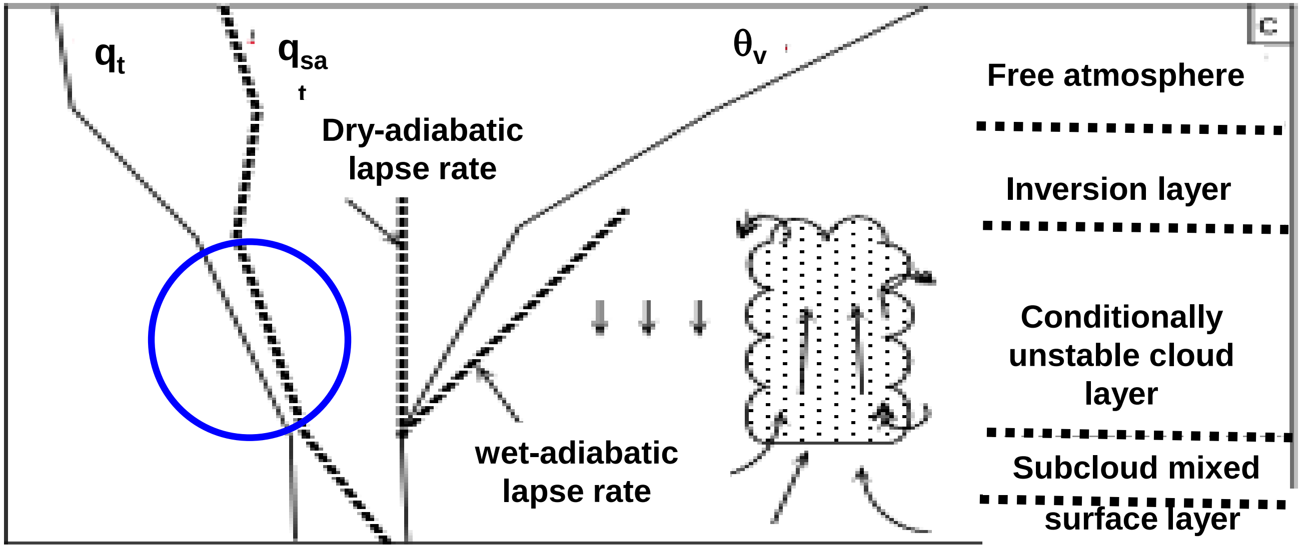
$\overline{(w'q_v')_0}, \Delta q_t, z_b, \Delta F$

Cloudy boundary layers

Stephan de Roode, Ph.D thesis



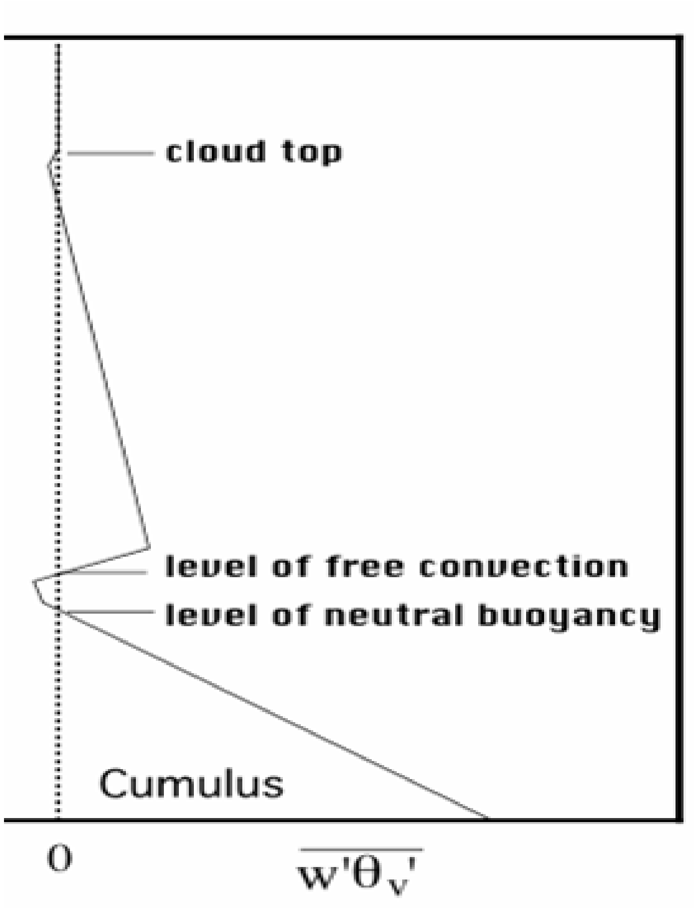
Stratocumulus topped PBL

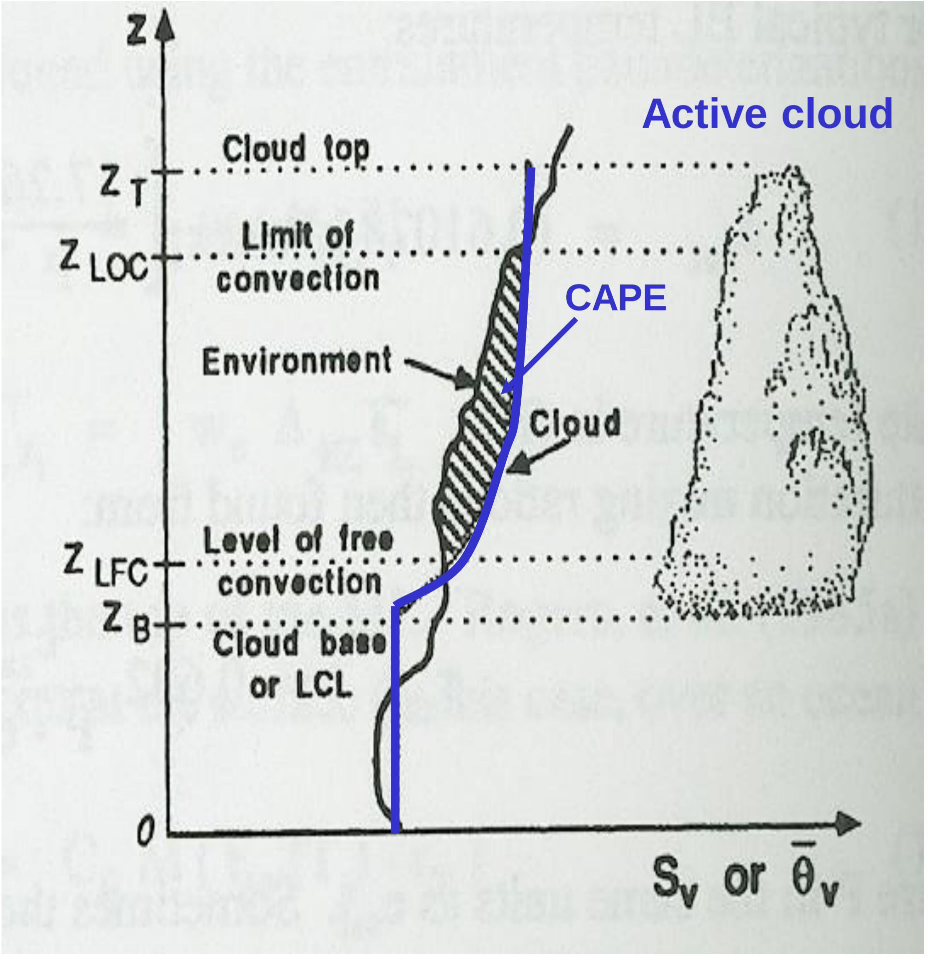


Cumulus PBL

Cumulus capped boundary layers

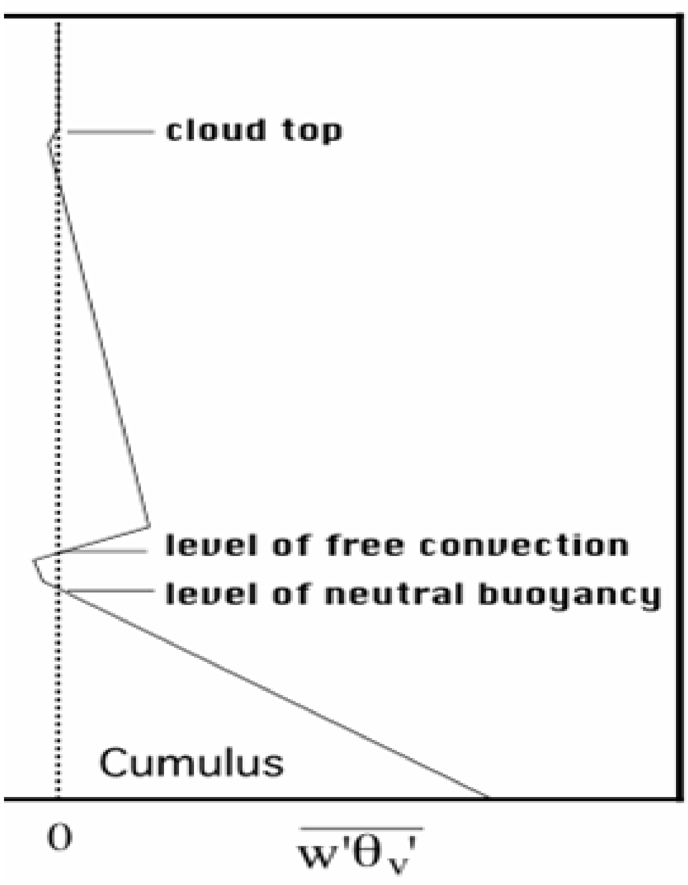
☞Buoyancy is the main mechanism that forces cloud to rise





Cumulus capped boundary layers

☞ Buoyancy is the main mechanism that forces cloud to rise



☞ Represented by mass flux convective schemes $M_c(\psi_u - \psi_d) = k\overline{w'\psi'}$

☞ Decomposition: cloud + environment

☞ Lateral entrainment/detrainment rates prescribed

☞ Key parameters: $H\,,\, z_b\,,\, \overline{(w'\theta_v')_0}\,,\, \overline{(w'q_v')_0}$

$$\left(\frac{\partial\theta_v}{\partial z}\right)_{environ.}, \left(\frac{\partial q_v}{\partial z}\right)_{environ.}$$

PBL: Summary

- Characteristics :
  - several thousands of meters – 2-3 km above the surface
  - turbulence, mixed layer
  - convection
  - Reynolds framework

- Classification:
  - neutral (extremely rare)
  - stable (nocturnal)
  - convective (mostly diurnal)

- Clear convective

- Cloudy (stratocumulus or cumulus)
  - Importance of boundary layer clouds (Earth radiative budget)
  - Small liquid water contents, difficult to measure

Bibliography

- Deardorff, J.W. (1973) *Three-dimensional numerical modeling of the planetary boundary layer*, In Workshop on Micrometeorology, D.A. Haugen (Ed.), American Meteorological Society, Boston, 271-311

- P. Bougeault, V. Masson, Processus dynamiques aux interfaces sol-atmosphere et ocean-atmosphere, cours ENM

- Nieuwstad, F.T.M., *Atmospheric boundary-layer processes and influence of inhomogeneos terrain*. In *Diffusion and transport of pollutants in atmospheric mesoscale flow fields* (ed. by Gyr, A. and F.S. Rys), Kluwer Academic Publishers, Dordrecht, The Netherlands, 89-125, 1995.

- Stull, R. B. (1988) *An introduction to boundary layer meteorology*, Kluwer Academic Publisher, Dordrecht, The Netherlands.

- S. de Roode (1999), *Cloudy Boundary Layers: Observations and Mass-Flux Parameterizations*, Ph.D. Thesis

- R. Wood (2012), Stratocumulus Clouds, Monthly Weather Review 2012 140:8, 2373-2423

- Wyngaard, J.C. (1992) *Atmospheric turbulence*, Annu. Rev. Fluid Mech. 24, 205-233