Planetary Boundary Layer 1

Introduction to boundary layers and turbulence

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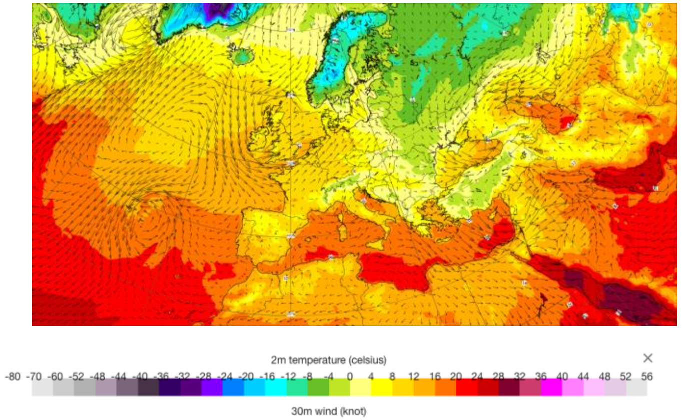
- Definition and description of the planetary boundary layer (PBL)
- Types of turbulence and Richardson number
- What do we need from a turbulence parametrization?
- Reynolds decomposition
- Diurnal cycle of the PBL and fluxes
- Cloudy and clear convective PBLs

Importance of the planetary boundary layer

It’s where we live!

We care about forecasting quantities in the boundary layer (temperature, winds)



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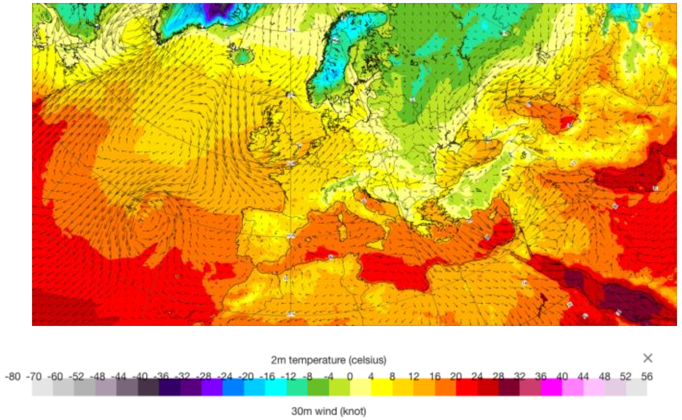

It is where exchange between the surface and upper atmosphere occurs

e.g. carbon-dioxide from plants / human activity, moisture from the Earth's surface, cloud formation

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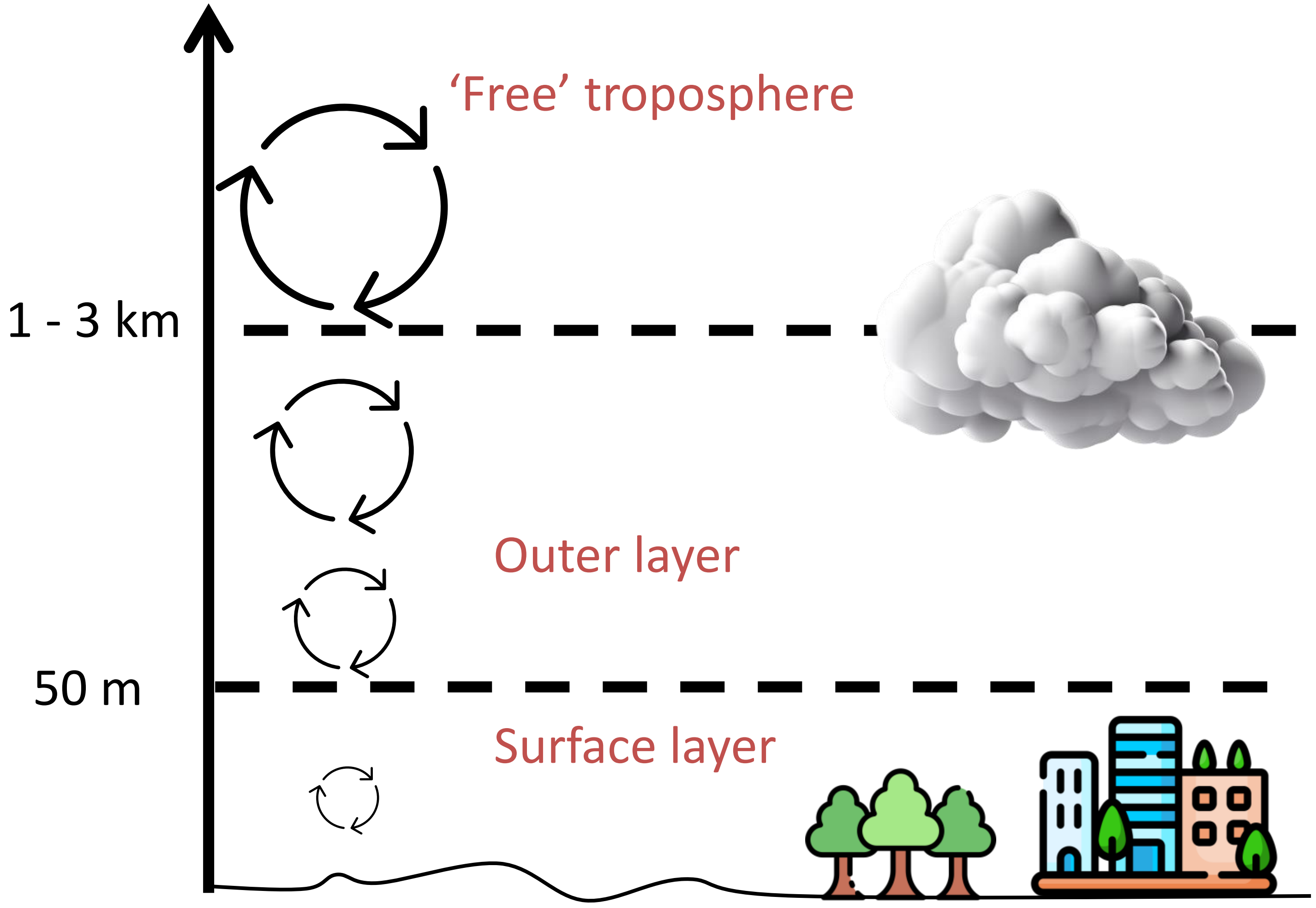
Definition of the planetary boundary layer

Layer of atmosphere directly influenced by the presence of the Earth's surface.

The surface effects (friction, cooling, heating or moistening) are felt on time scales of hours.

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.



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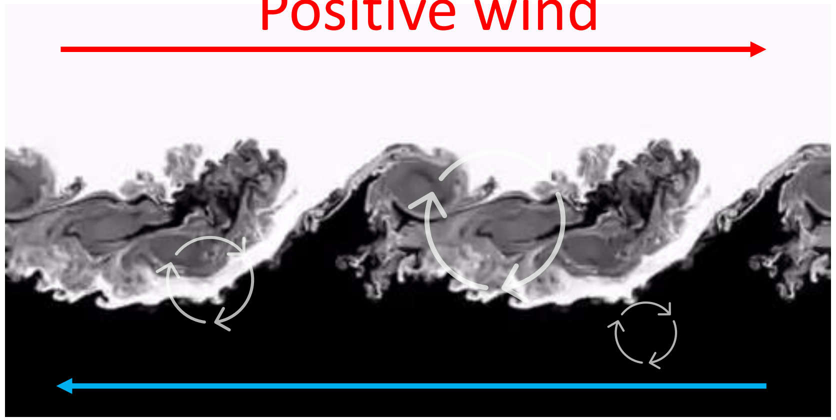
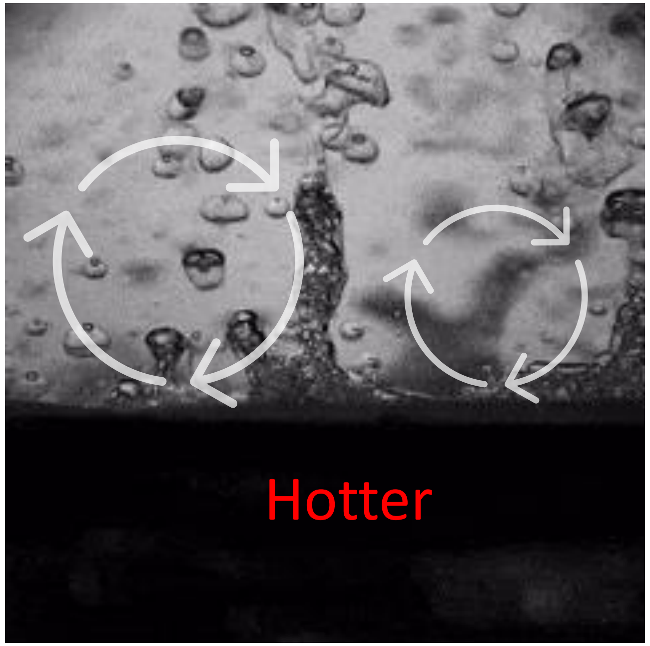
Types of turbulence

Shear turbulence: $\left|\frac{dU}{dz}\right|$



Convective turbulence: $\mathrm{N}^2 = \frac{\mathrm{g}}{\theta}\frac{d\theta}{dz}$



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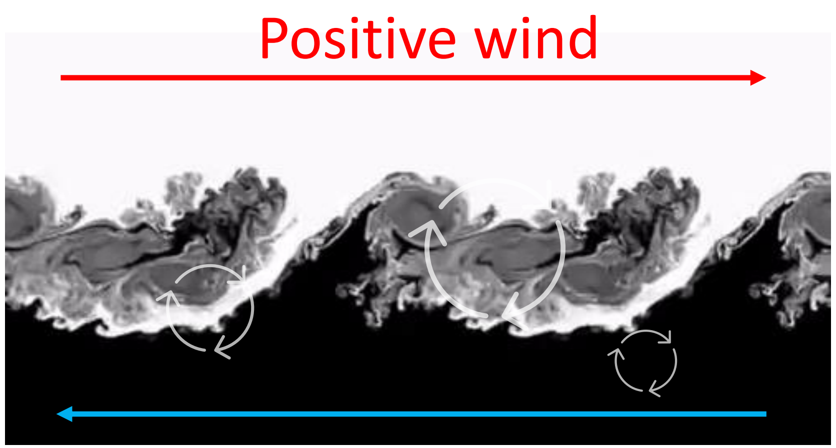

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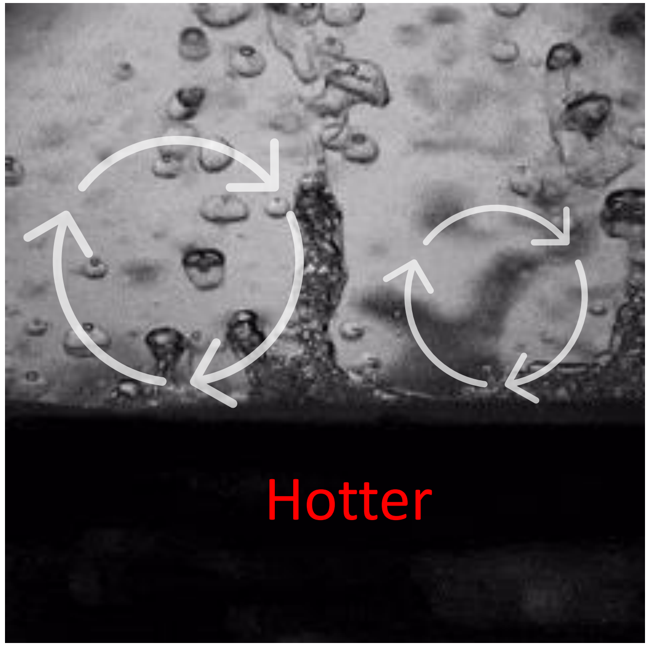

$$Ri = \frac{N^2}{\left|\frac{dU}{dz}\right|^2}$$

Richardson number provides a measure of the relative importance of convective and shear turbulence

$Ri < 0$, convectively unstable
$Ri \sim 0$, neutral
$Ri > 0$, stable but subject to shear instability

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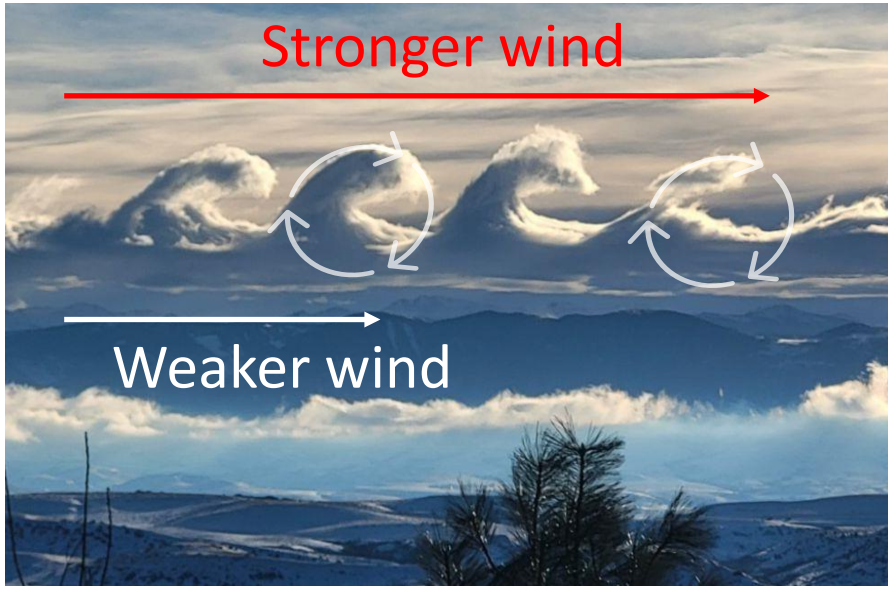
Types of turbulence

Shear turbulence: $\left|\frac{dU}{dz}\right|$



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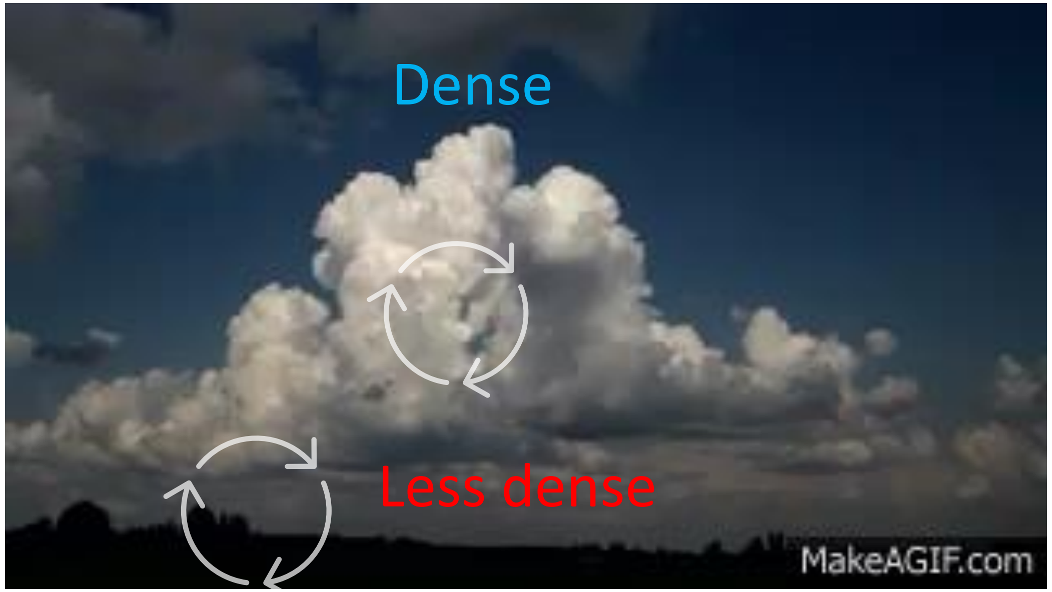

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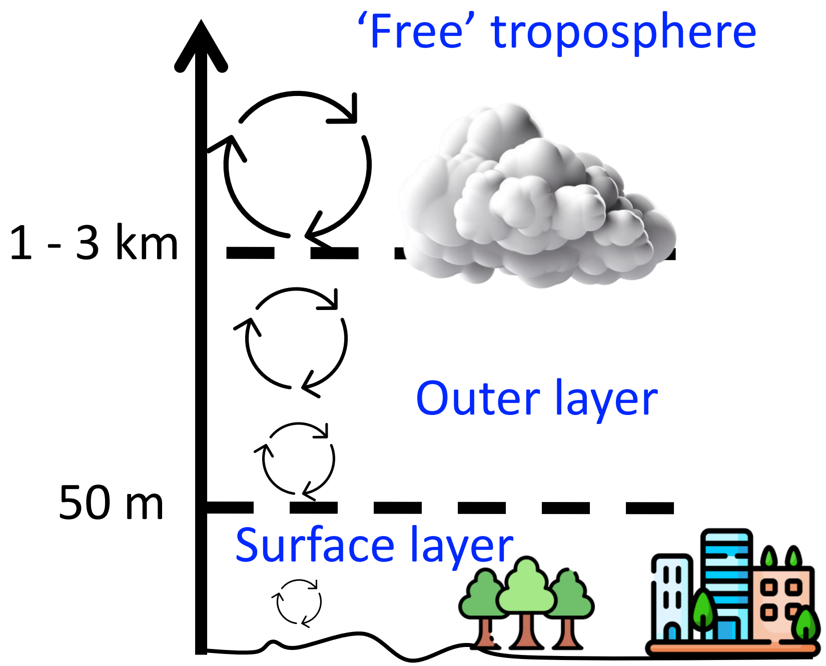
- Provide turbulent fluxes of heat, momentum, moisture (and tracers) between the surface and the upper atmosphere
- Provide turbulent mixing throughout the entire atmosphere – the mixed layer, the cloud layer and the stratosphere
- Account for differences in stability, surface properties and clouds
- Provide profiles of winds and temperatures at the surface, where the model does not resolve in the vertical



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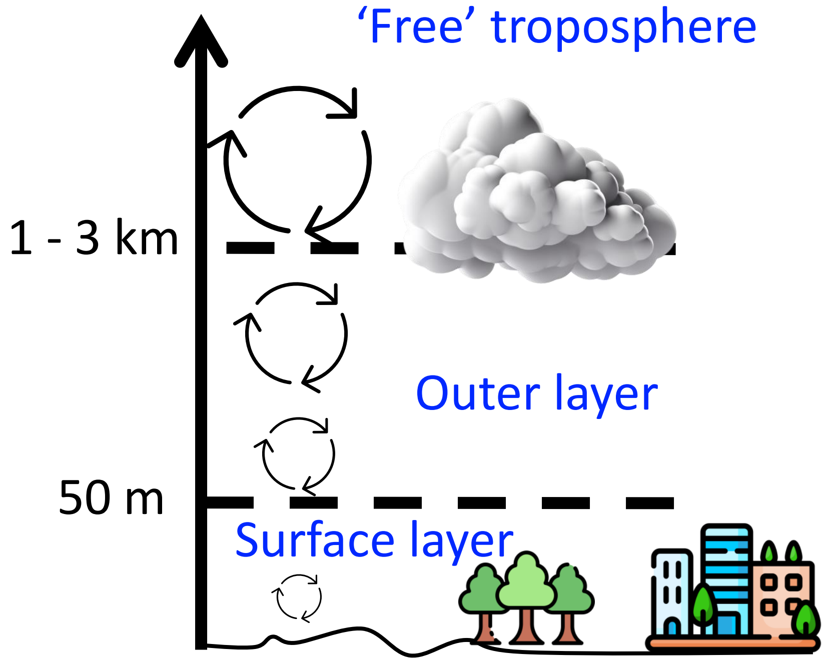

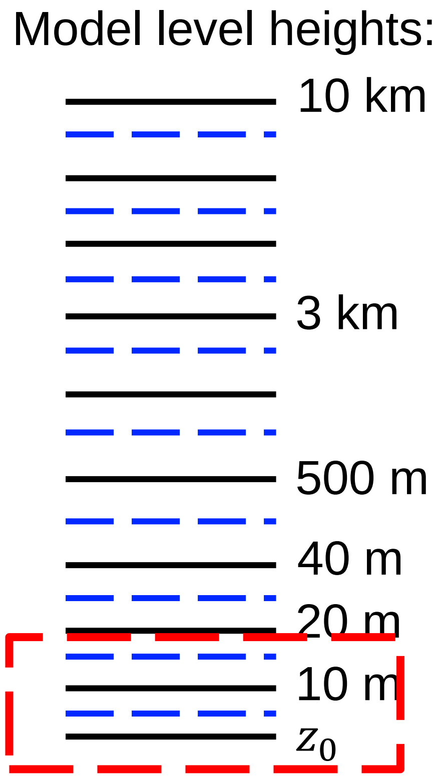

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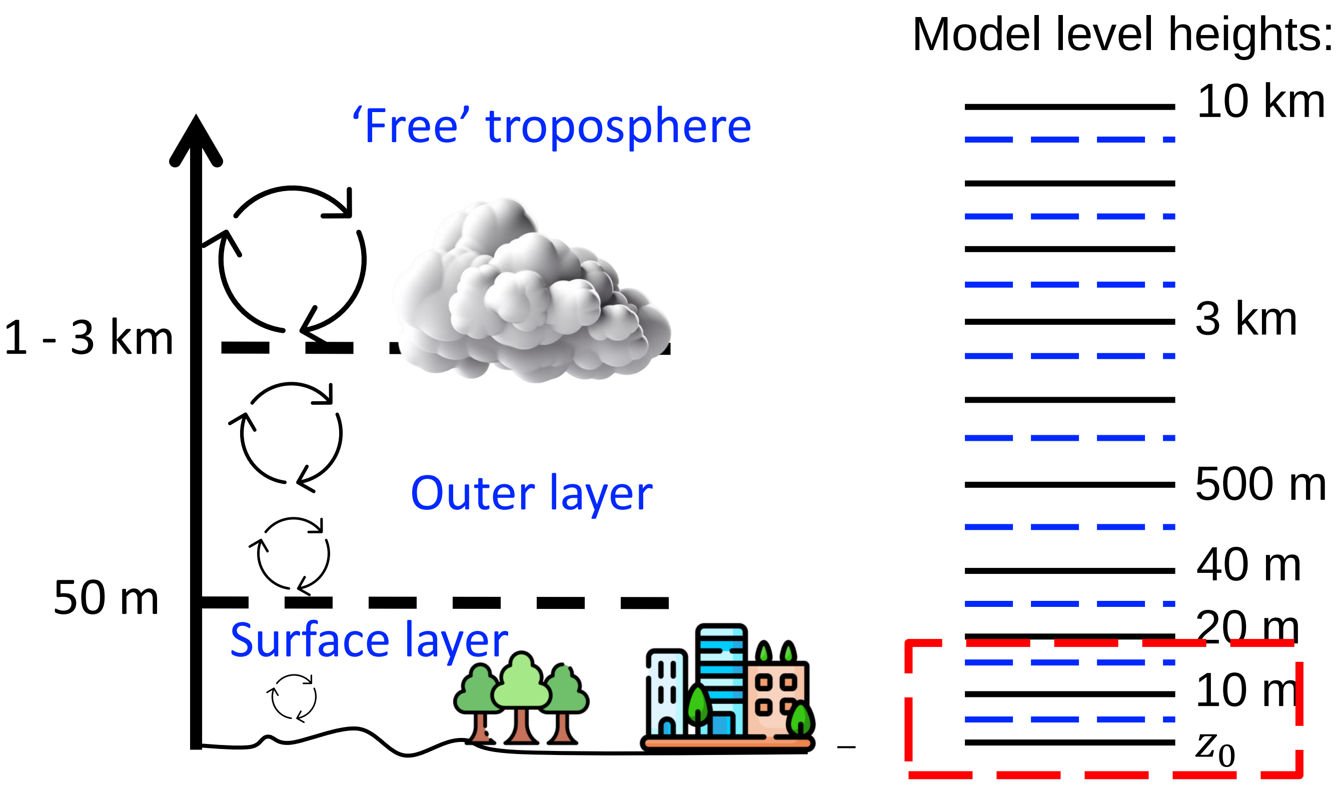
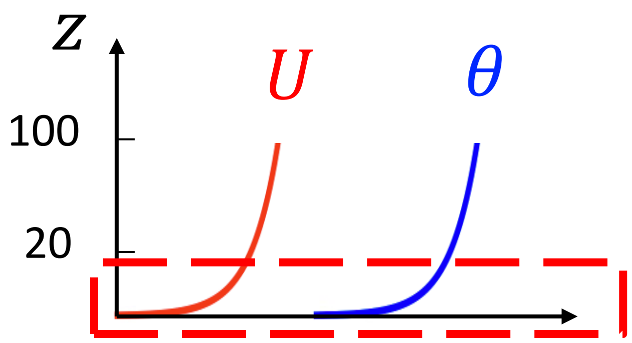


- Model does not resolve surface layer
- There are strong gradients and is where people live
- Requires diagnosis of profiles below 10m



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Turbulence in the governing equations

Governing equations - simplified

Momentum

$$\frac{\partial u}{\partial t} = -\frac{1}{\rho}\nabla \cdot (\rho u \boldsymbol{u}) + fv - \frac{1}{\rho}\frac{\partial p}{\partial x} + \nu \nabla^2 u$$

$$\frac{\partial v}{\partial t} = -\frac{1}{\rho}\nabla \cdot (\rho v \boldsymbol{u}) + -fu - \frac{1}{\rho}\frac{\partial p}{\partial y} + \nu \nabla^2 v$$

$$\frac{1}{\rho}\frac{\partial p}{\partial r} = -\rho g$$

Mass Continuity

$$\nabla \cdot \boldsymbol{u} = 0$$

No density variations

(Boussinesq)

Thermodynamics

$$\frac{\partial \theta}{\partial t} = -\frac{1}{\rho}\nabla \cdot (\rho \theta \boldsymbol{u}) + S_\theta + \nu \nabla^2 \theta$$

Moisture

$$\frac{\partial q}{\partial t} = -\frac{1}{\rho}\nabla \cdot (\rho q \boldsymbol{u}) + S_q + \nu \nabla^2 q$$

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Large scale terms

Molecular viscosity

Fluxes

Sources and sinks (e.g. heating and cooling from radiation)

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Molecular viscosity<< other terms

Fluxes- small+large scale processes

Sources and sinks (e.g. heating and cooling from radiation)

Direct numerical simulations at high enough resolution / analytic solutions to capture turbulence fully are not currently possible

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Reynolds decomposition of fluxes

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Fluxes = small + large scale processes

Reynolds decomposition of fluxes

A variable ϕ:

$$\frac{\partial \phi}{\partial t} = -\frac{1}{\rho}\nabla \cdot (\rho \phi \boldsymbol{u})$$

Fluxes = small + large scale processes

Steps:

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Reynolds decomposition of fluxes

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$$\frac{\partial \phi}{\partial t} = -\frac{1}{\rho}\left[\frac{\partial \rho \phi u}{dx} + \frac{\partial \rho \phi v}{dy} + \frac{\partial \rho \phi w}{dz}\right]$$

Fluxes = small + large scale processes

Steps:

1. Expand fluxes

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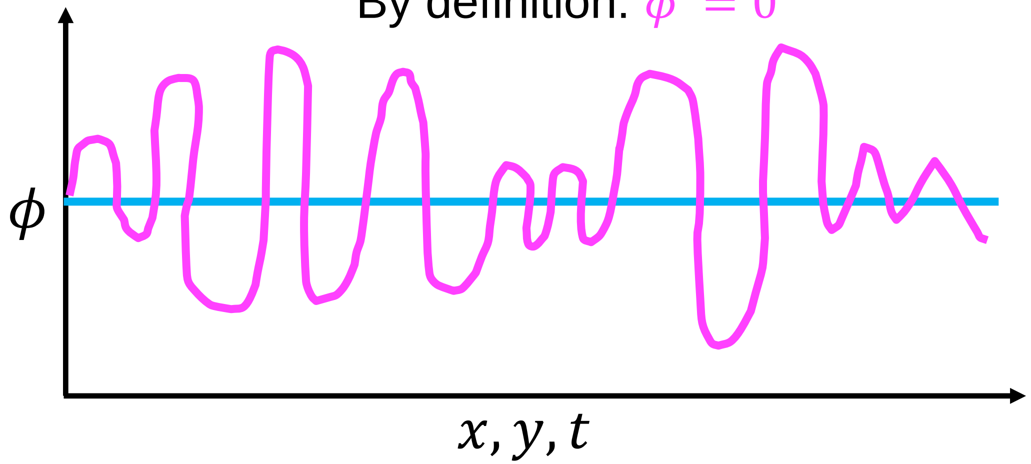
$$\phi = \overline{\phi} + \phi'$$

Large scale ($\overline{\phi}$) — Small scale (ϕ')

By definition: $\overline{\phi'} = 0$



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Steps:

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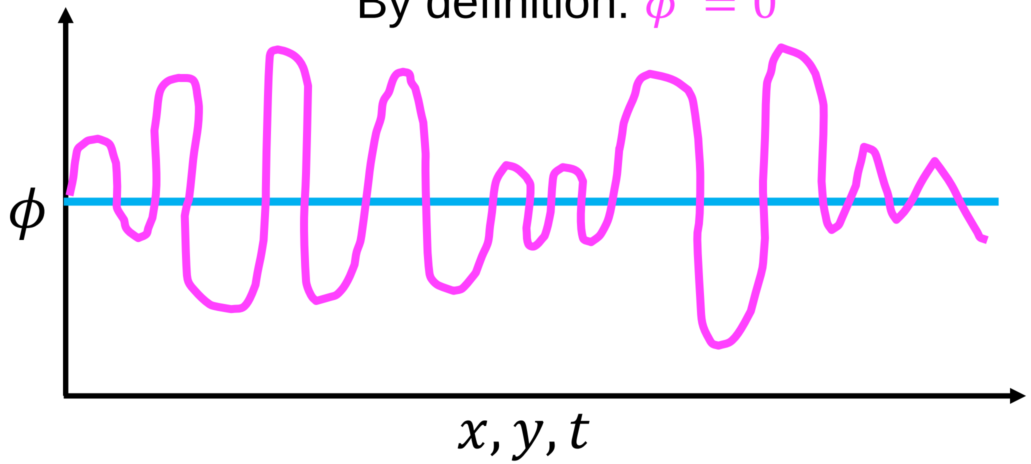

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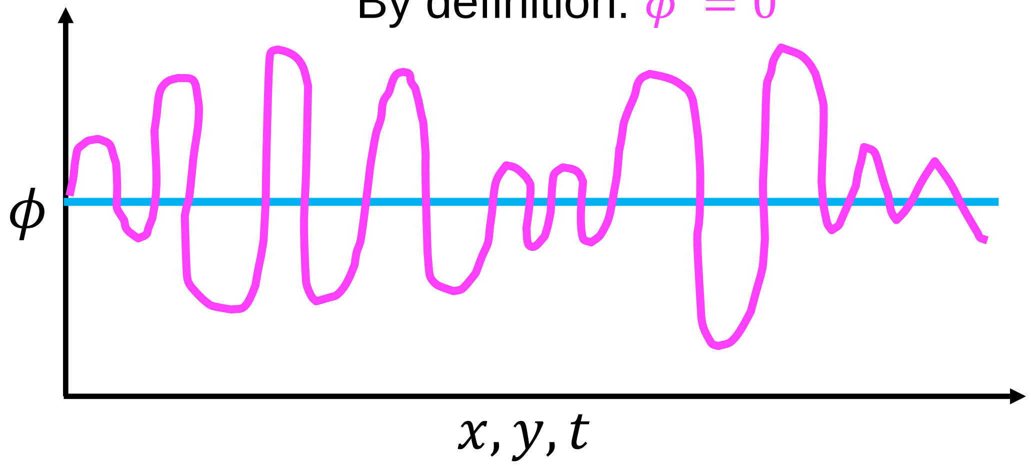

Fluxes = small + large scale processes

Steps:

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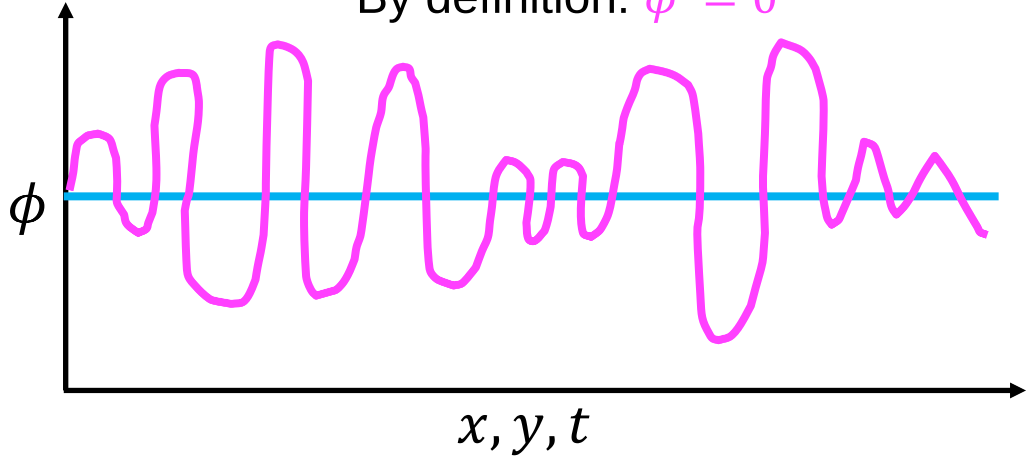

Fluxes = small + large scale processes

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Reynolds decomposition of fluxes

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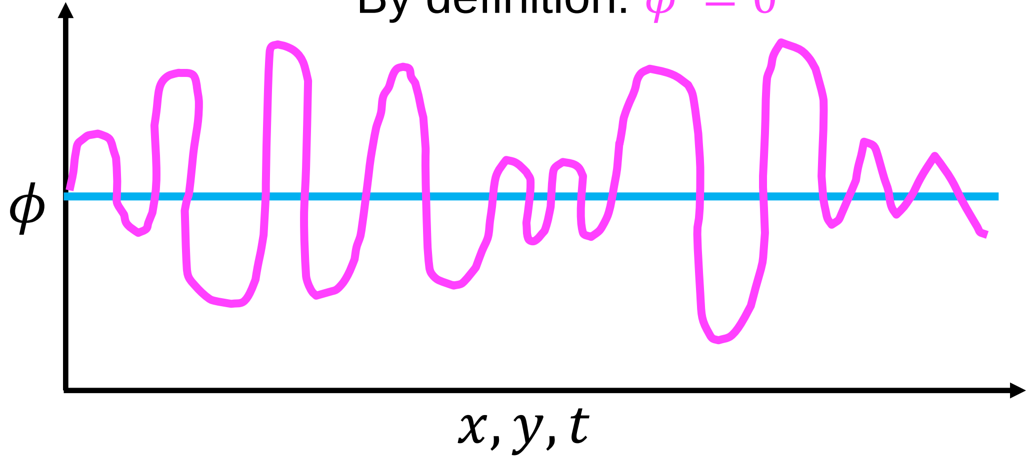

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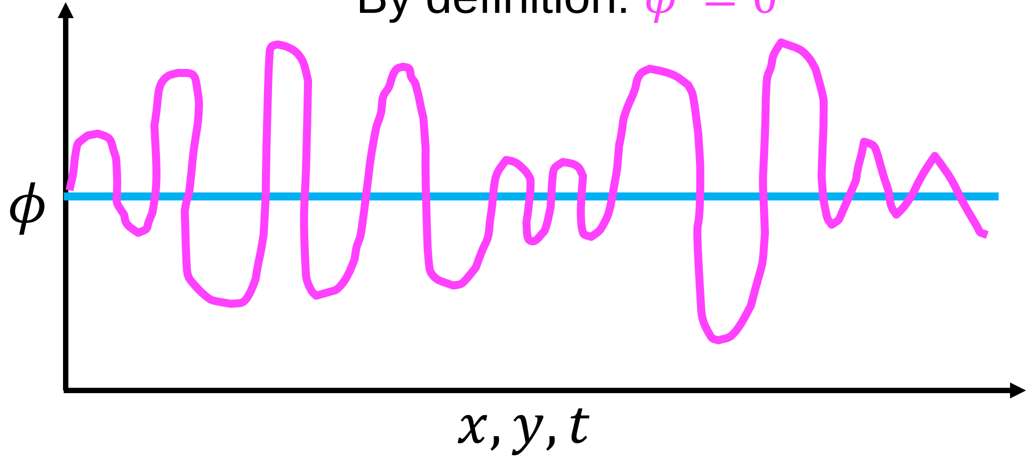

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$$\frac{\partial \overline{v}}{\partial t} = -\frac{1}{\rho}\left[\frac{\partial \rho \overline{v}\overline{u}}{dx} + \frac{\partial \rho \overline{v}\overline{v}}{dy} + \frac{\partial \rho \overline{v}\overline{w}}{dz} + \frac{\partial \rho \overline{v'w'}}{dz}\right]$$

Handled by model dynamics, i.e. resolved by the model grid

Thermodynamics

$$\frac{\partial \overline{\theta}}{\partial t} = -\frac{1}{\rho}\left[\frac{\partial \rho \overline{\theta}\overline{u}}{dx} + \frac{\partial \rho \overline{\theta}\overline{v}}{dy} + \frac{\partial \rho \overline{\theta}\overline{w}}{dz} + \frac{\partial \rho \overline{\theta'w'}}{dz}\right]$$

Moisture

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Reynolds decomposition of fluxes

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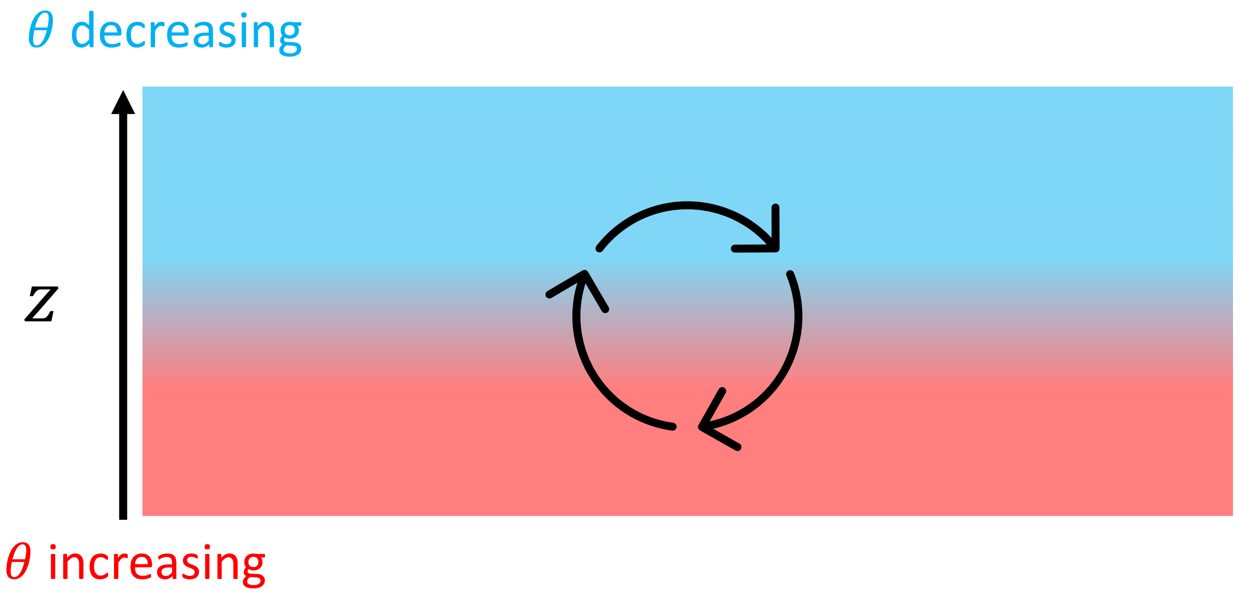
Small scale turbulent fluxes – must be parametrized

Reynolds decomposition of fluxes – what do the fluxes mean?

Horizontally homogenous fluid – only vertical variation
+ Turbulent eddy in the fluid



e.g. potential temperature gradient

$$\frac{\partial \theta}{\partial z} < 0 \text{ : unstable atmosphere}$$

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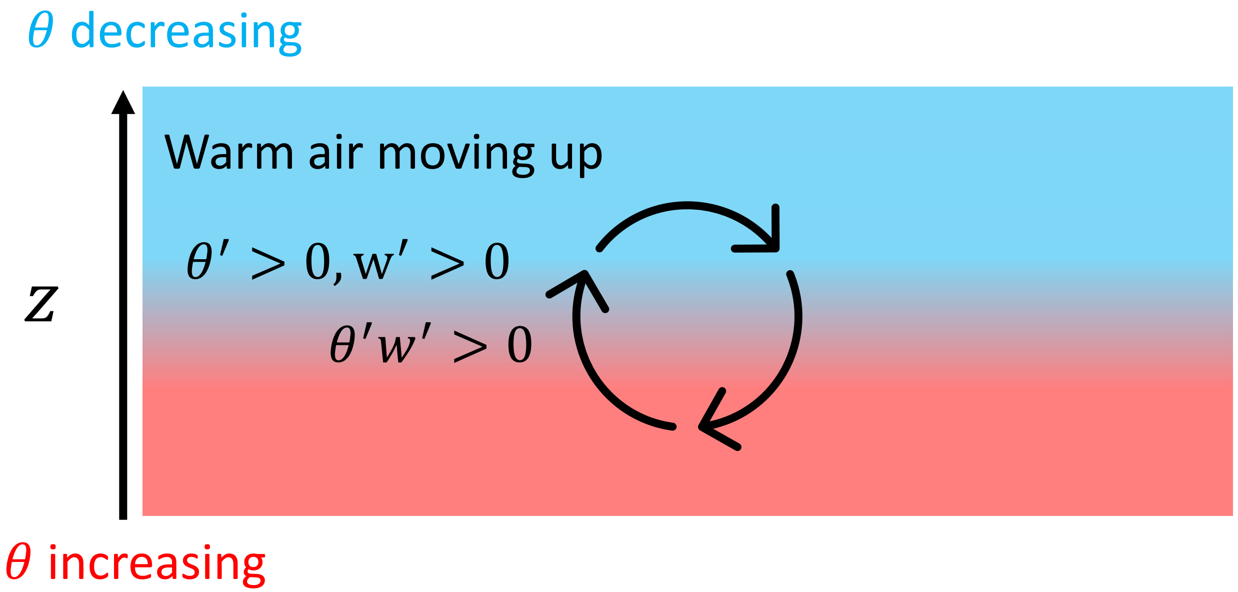

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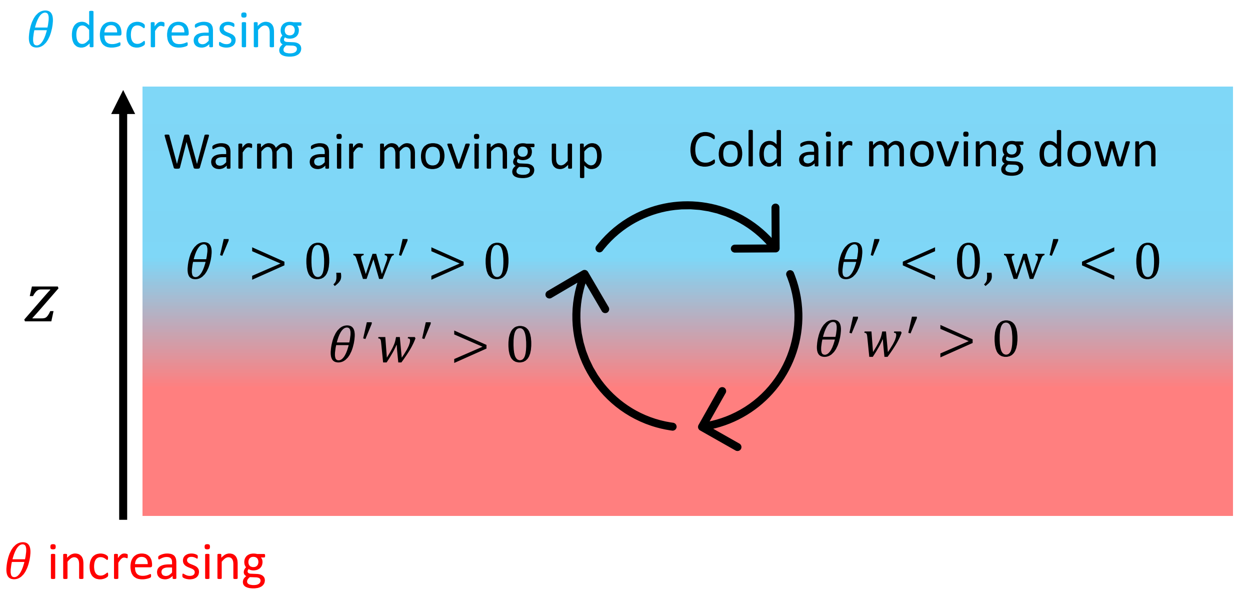

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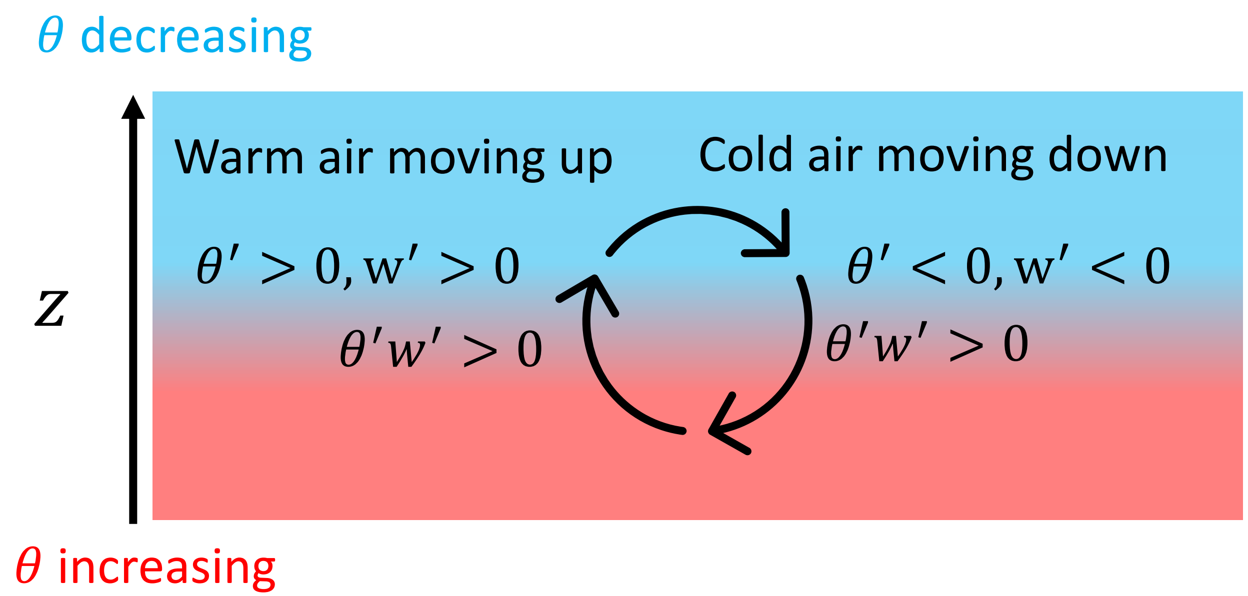

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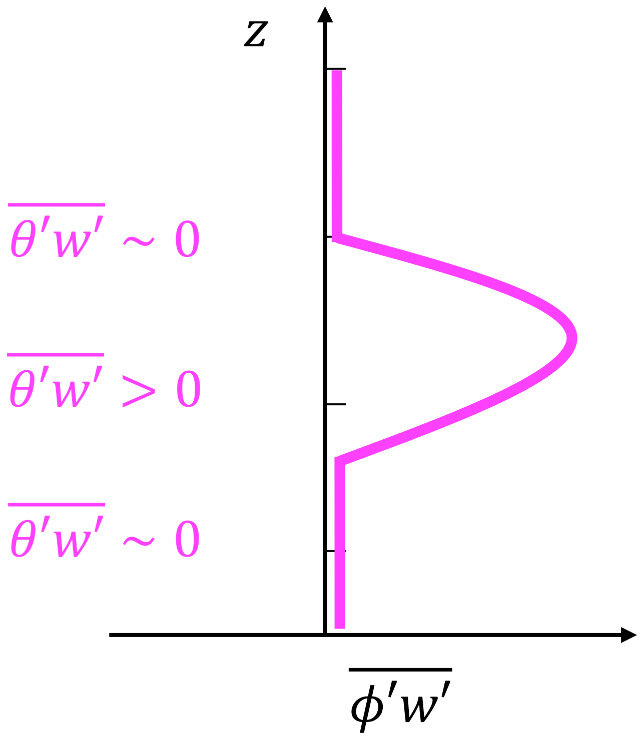

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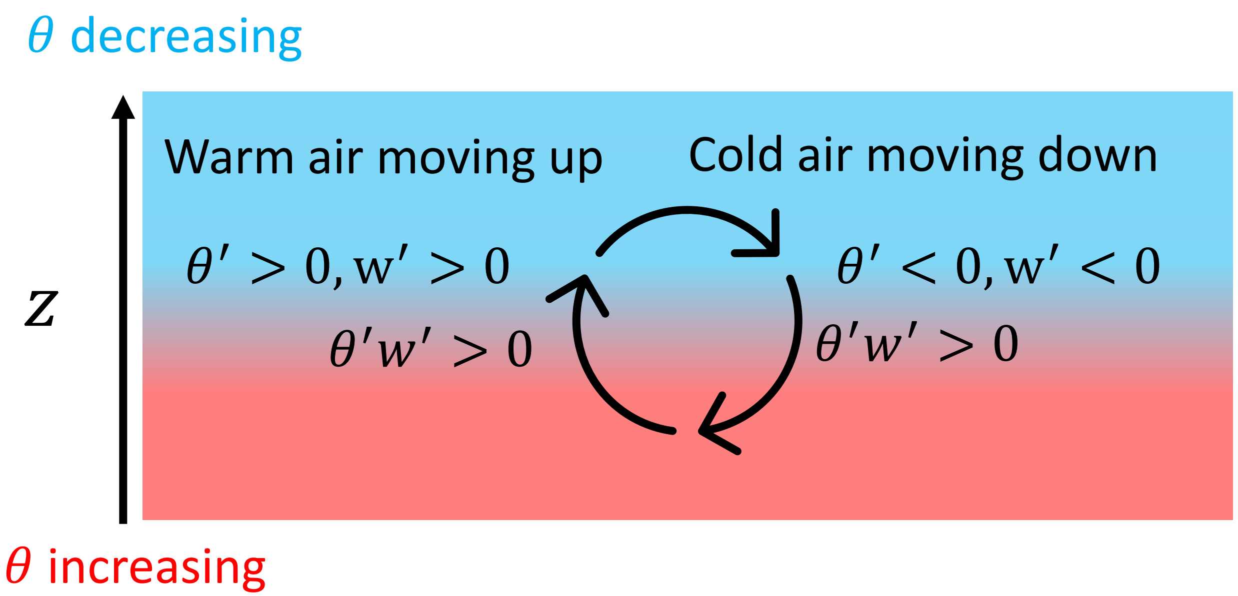
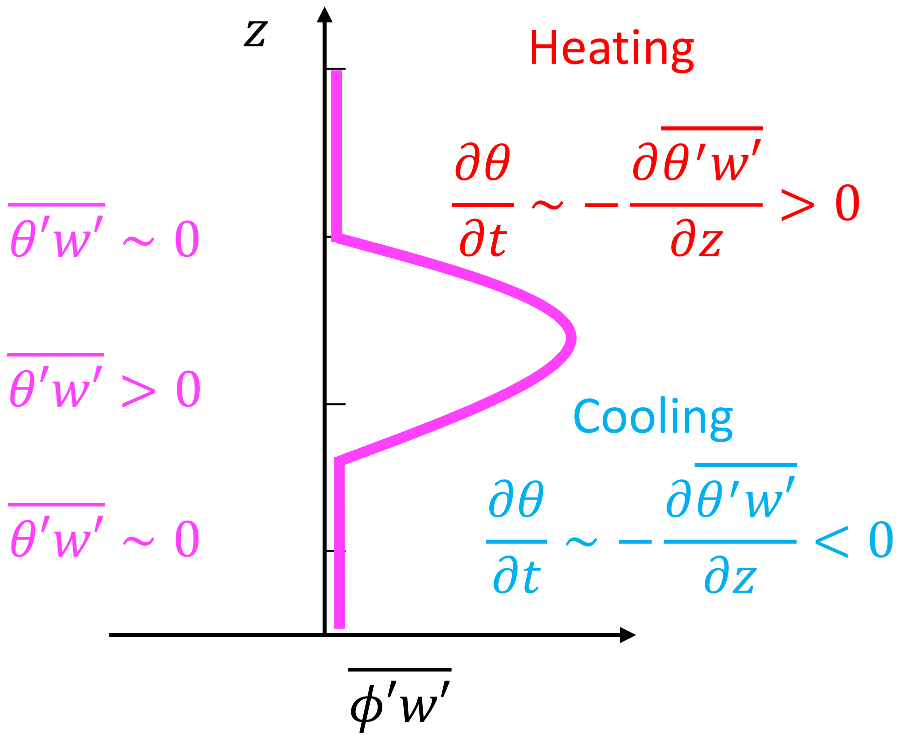


e.g. potential temperature gradient



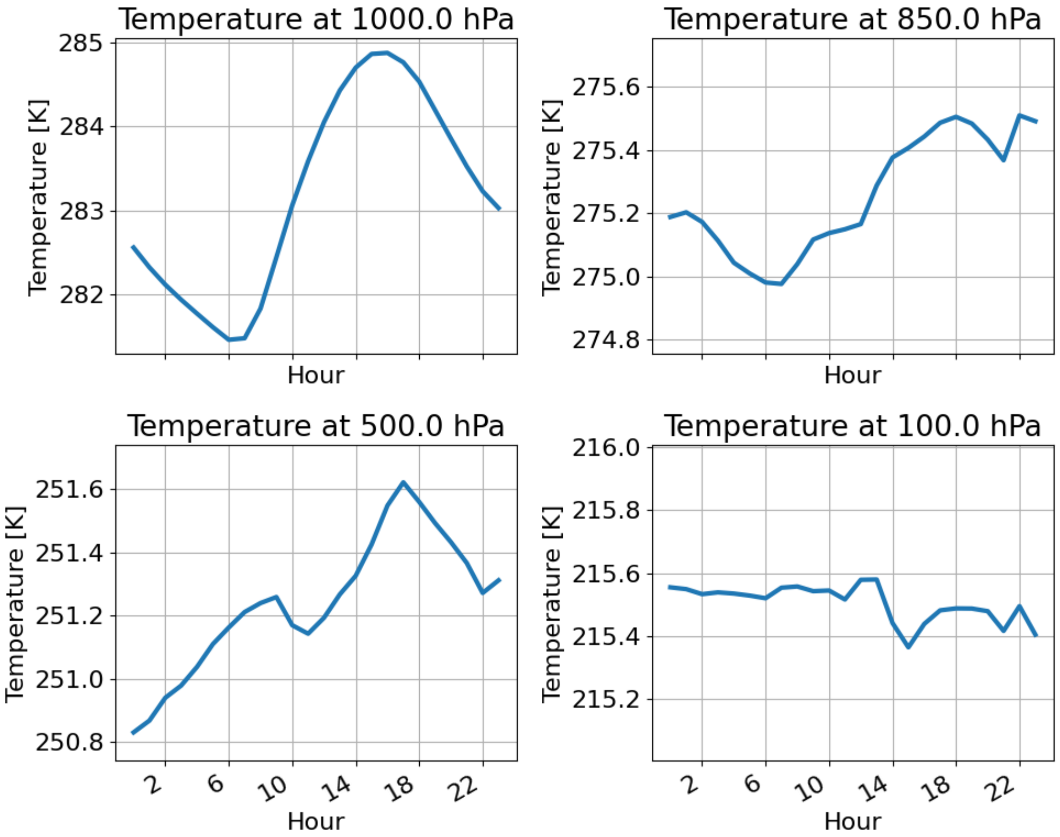
Acts to homogenize the fluid

$$\frac{\partial\theta}{\partial z} < 0 \text{ : unstable atmosphere}$$

Diurnal cycle of the planetary boundary layer

Diurnal cycle of PBL

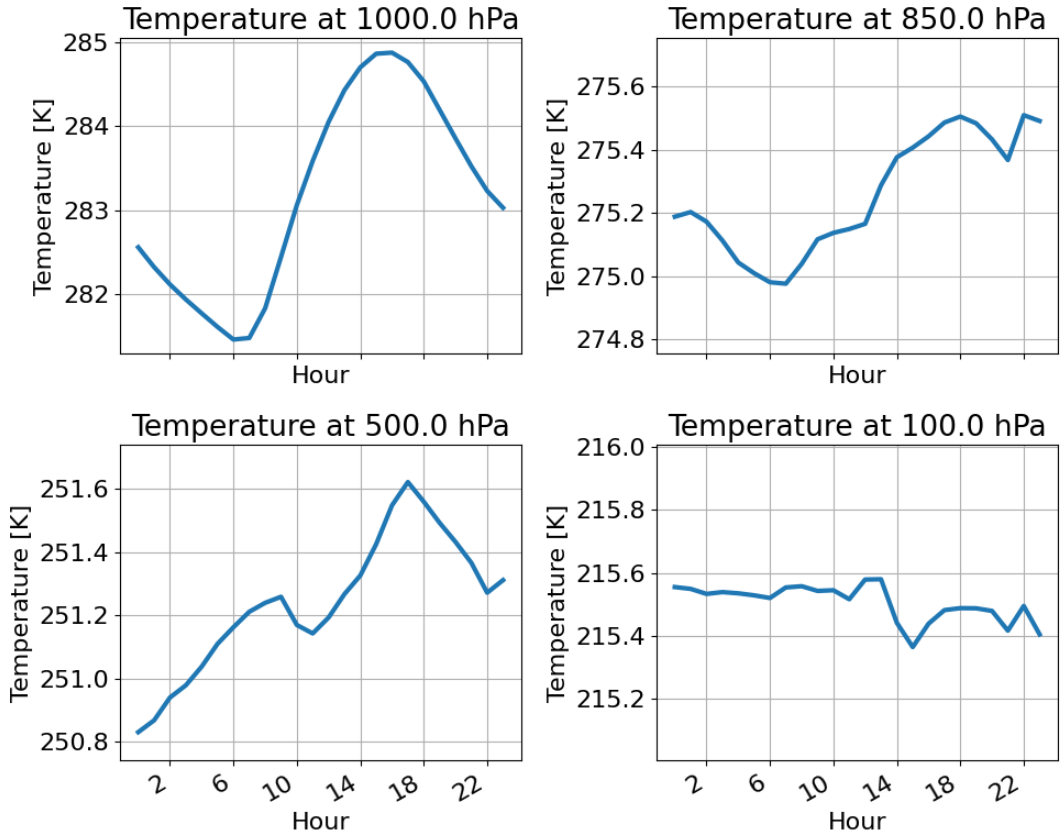
Temperature at Reading at various heights



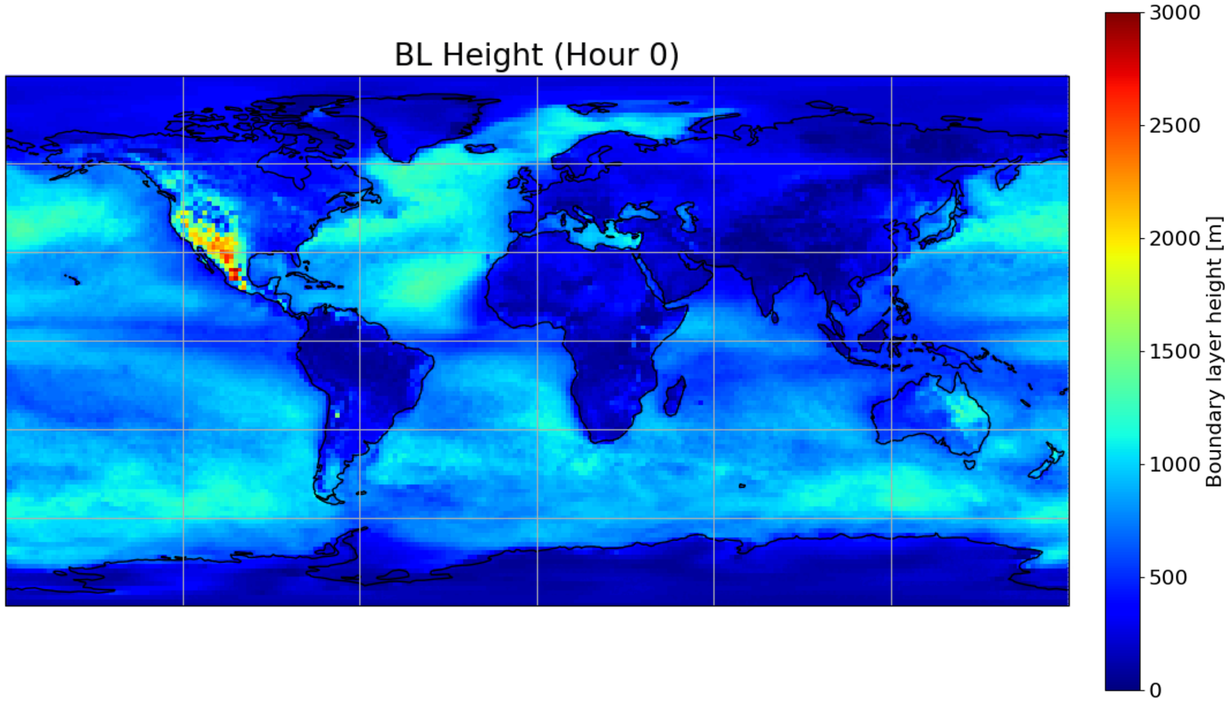
- Diurnal cycle weakens with height

Diurnal cycle of PBL

Temperature at Reading at various heights



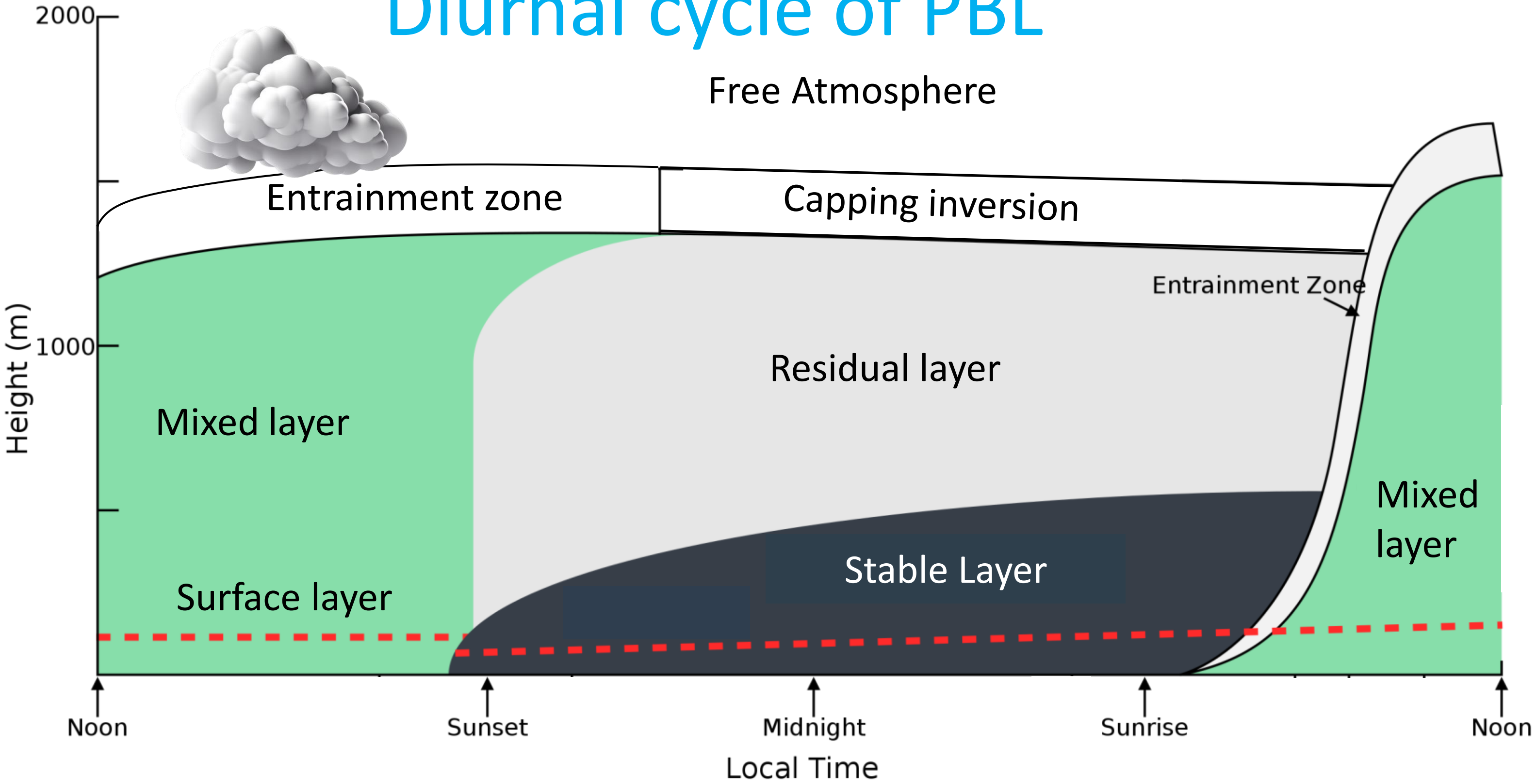
- Diurnal cycle weakens with height
- PBL height grows in the day due to convection (reaches ~ 2 km)
- Diurnal cycle much stronger over land than ocean

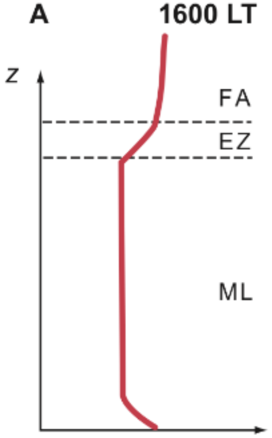


Diurnal cycle of PBL

$$Ri = \frac{N^2}{\left(\frac{dU}{dz}\right)^2}$$

Daytime: unstable near-surface and convective mixing occurs





$Ri < 0$

Free atmosphere

Entrainment zone

Mixed layer

Surface layer

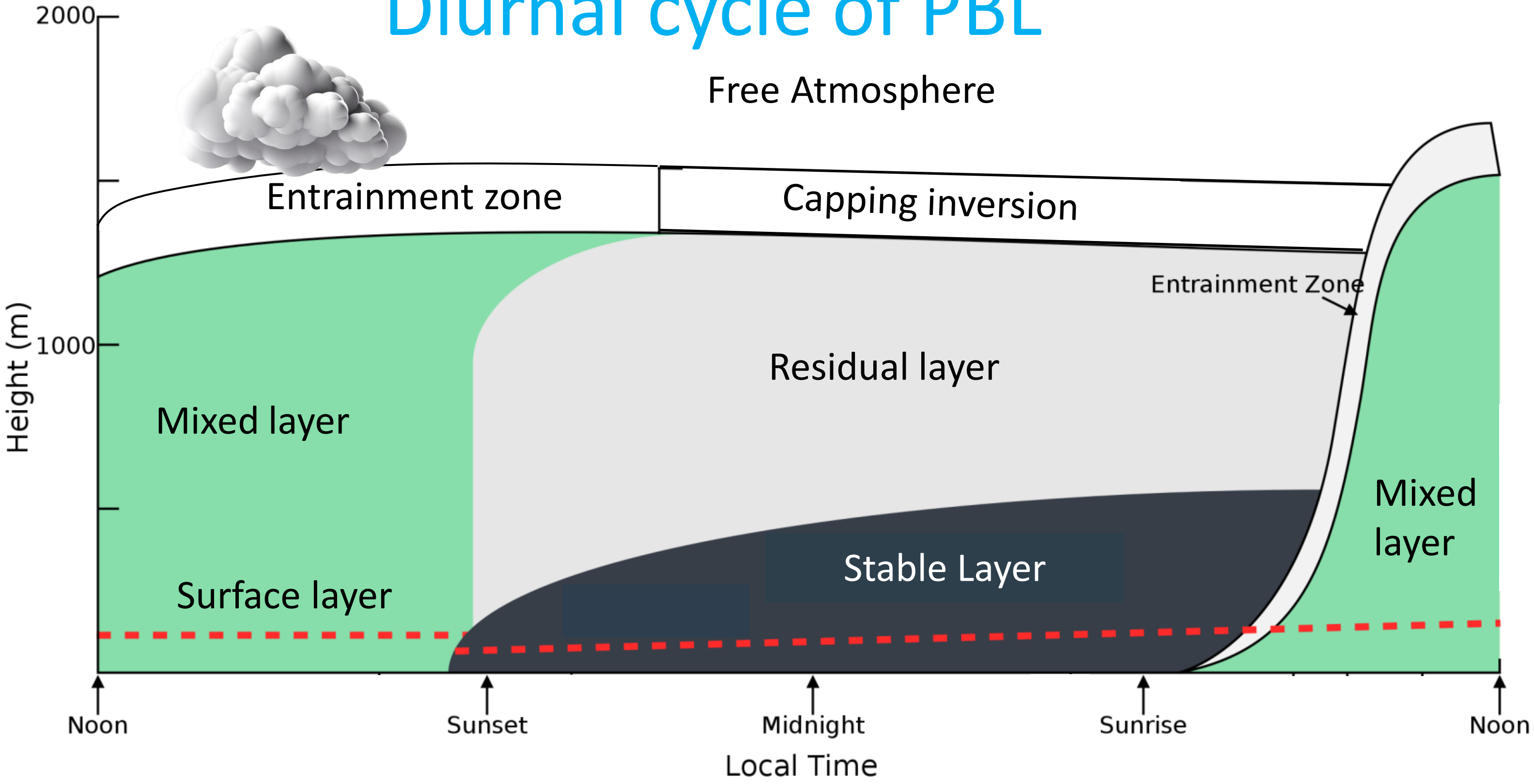
ECMWF

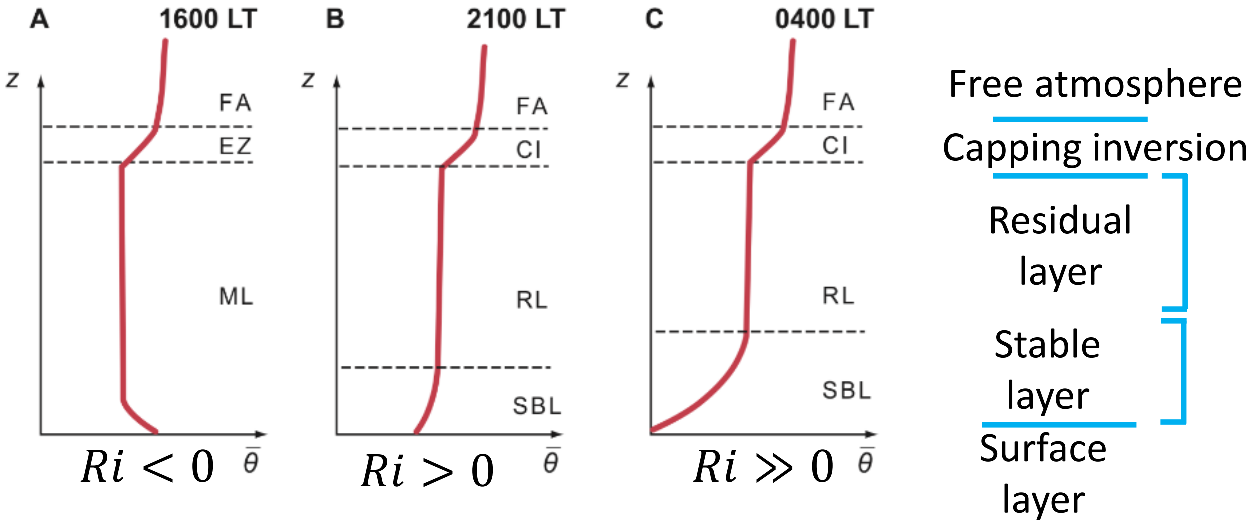
Diurnal cycle of PBL

$$Ri = \frac{N^2}{\left(\frac{dU}{dz}\right)^2}$$

Daytime: unstable near-surface and convective mixing occurs

Nighttime: stable near-surface with residual mixed layer





ECMWF

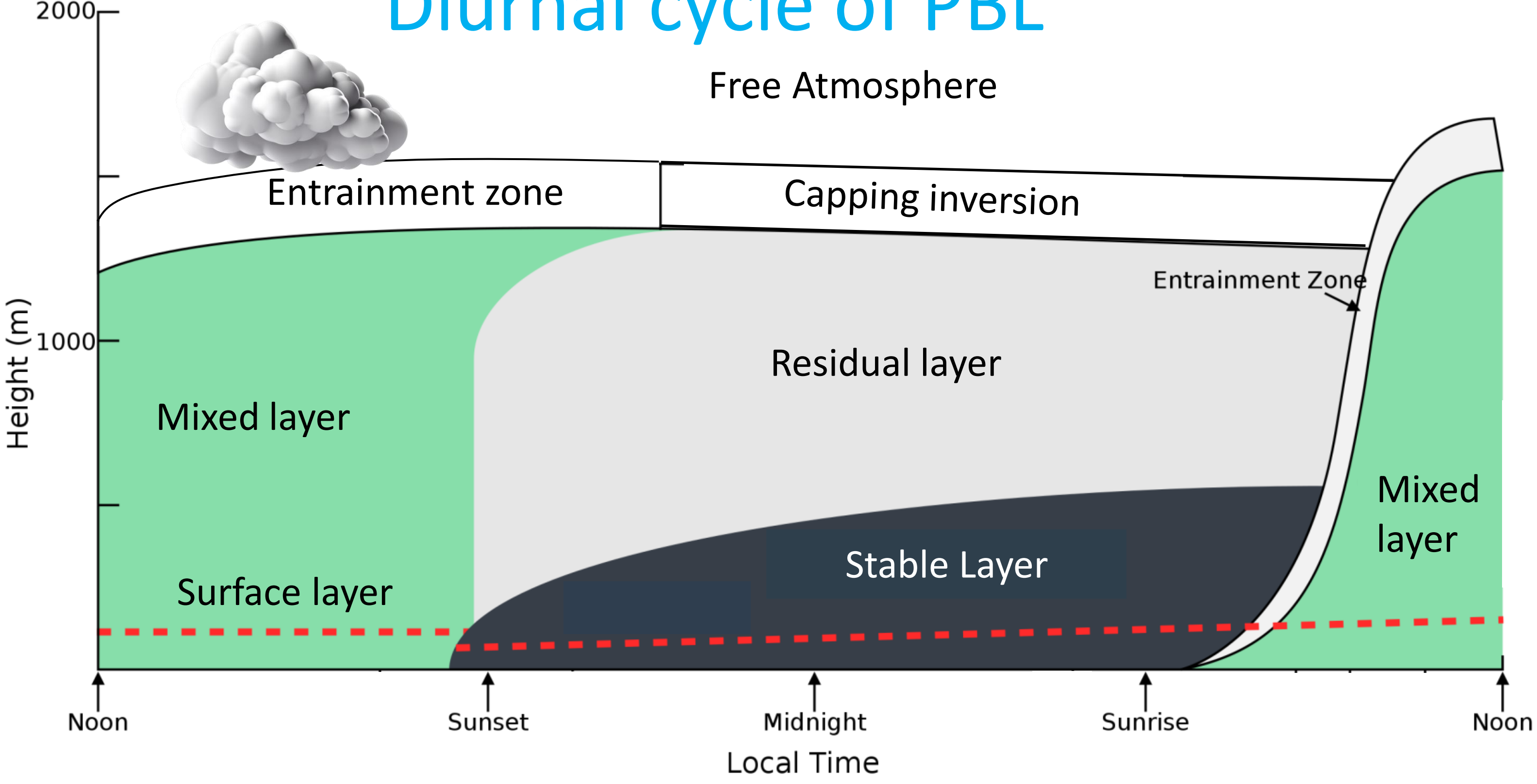
Diurnal cycle of PBL

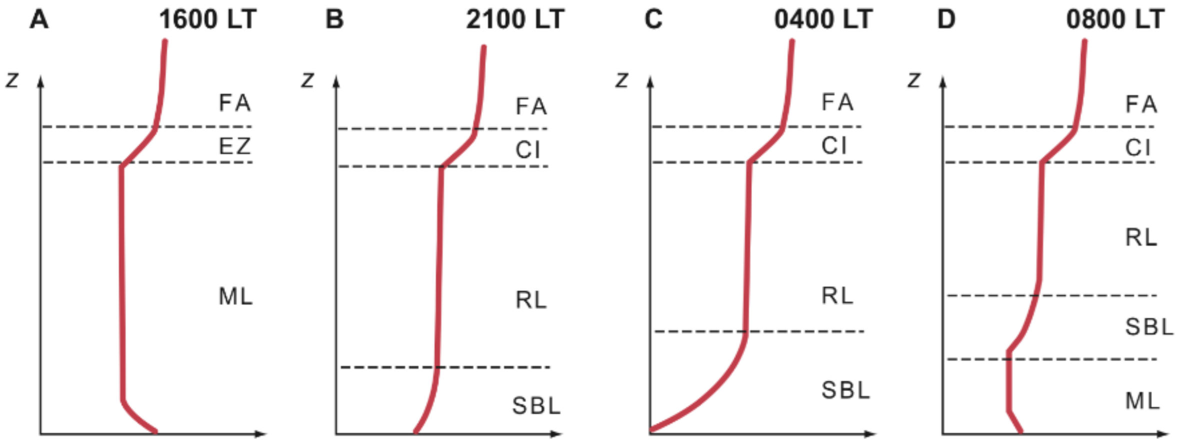
$$Ri = \frac{N^2}{\left(\frac{dU}{dz}\right)^2}$$

Daytime: unstable near-surface and convective mixing occurs

Nighttime: stable near-surface with residual mixed layer

Morning: unstable near-surface and mixed layer grows



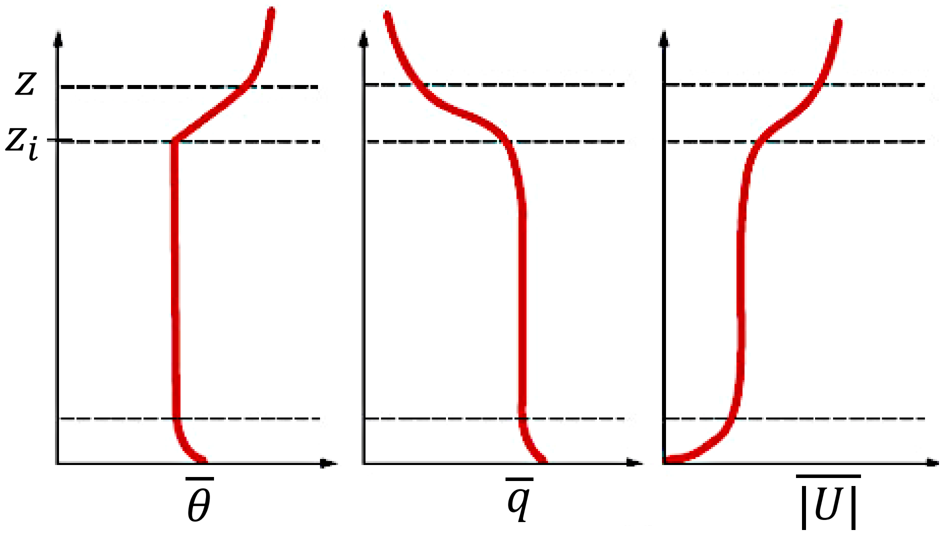


$Ri < 0$ $Ri > 0$ $Ri \gg 0$ $R < 0$

ECMWF

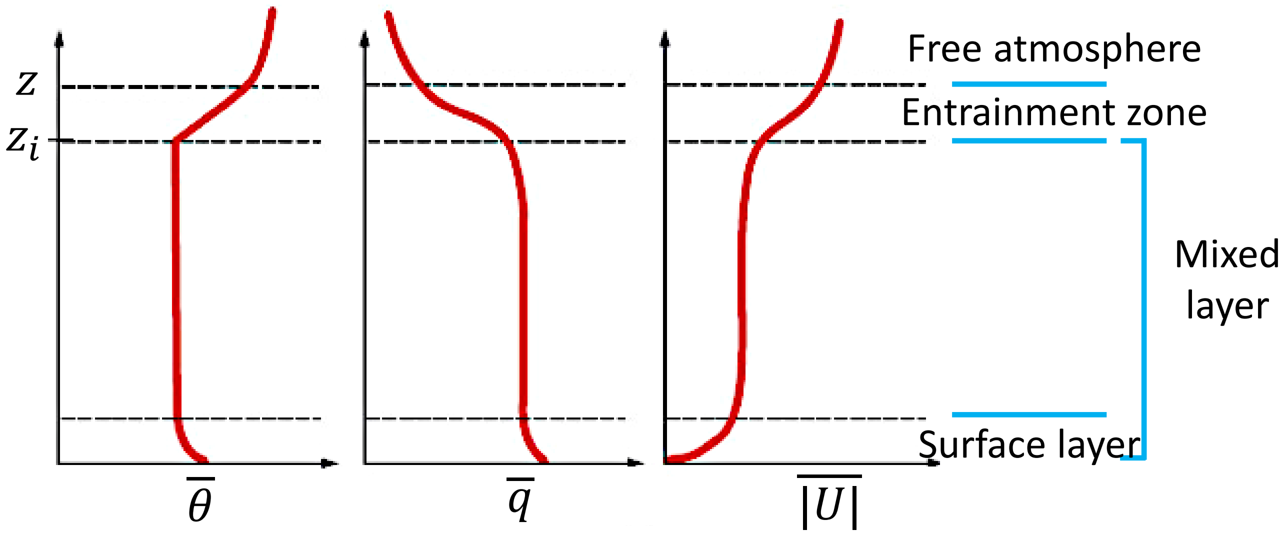
Diurnal cycle of PBL mean quantities and fluxes

Daytime



Diurnal cycle of PBL mean quantities and fluxes

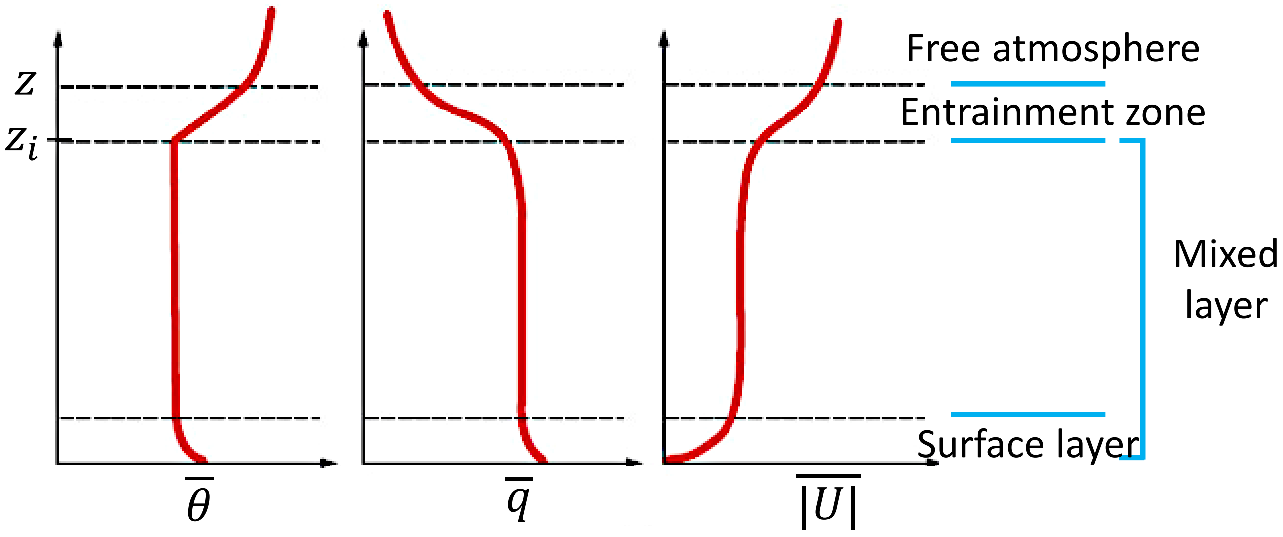
Daytime



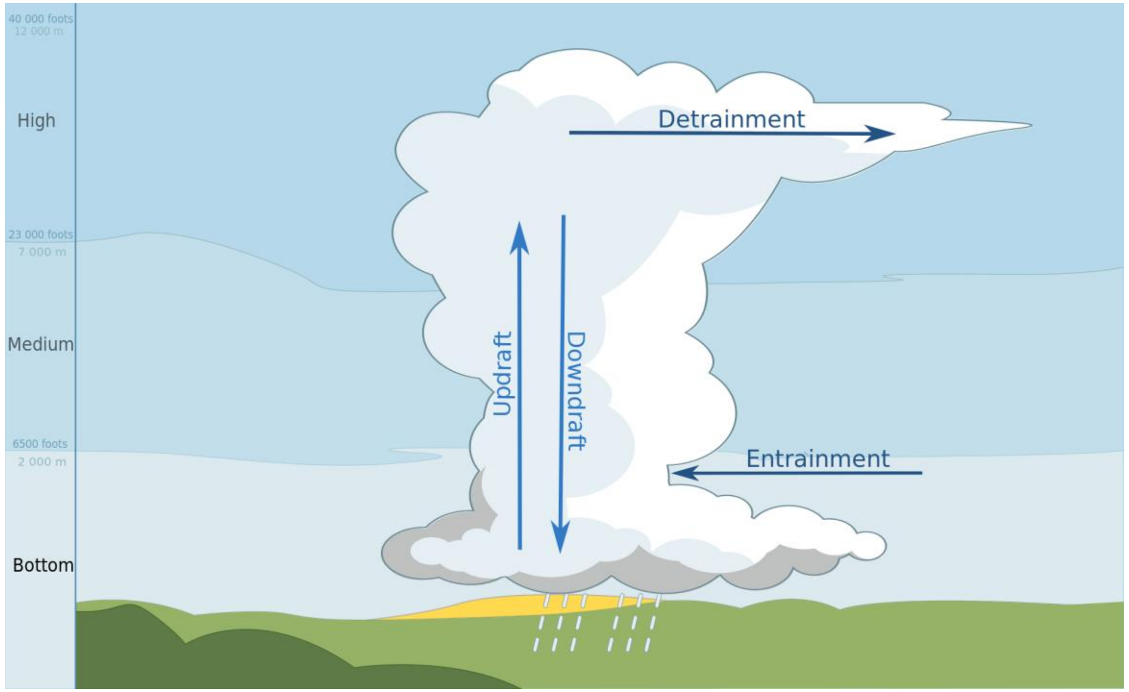
ECMWF

Diurnal cycle of PBL mean quantities and fluxes

Daytime

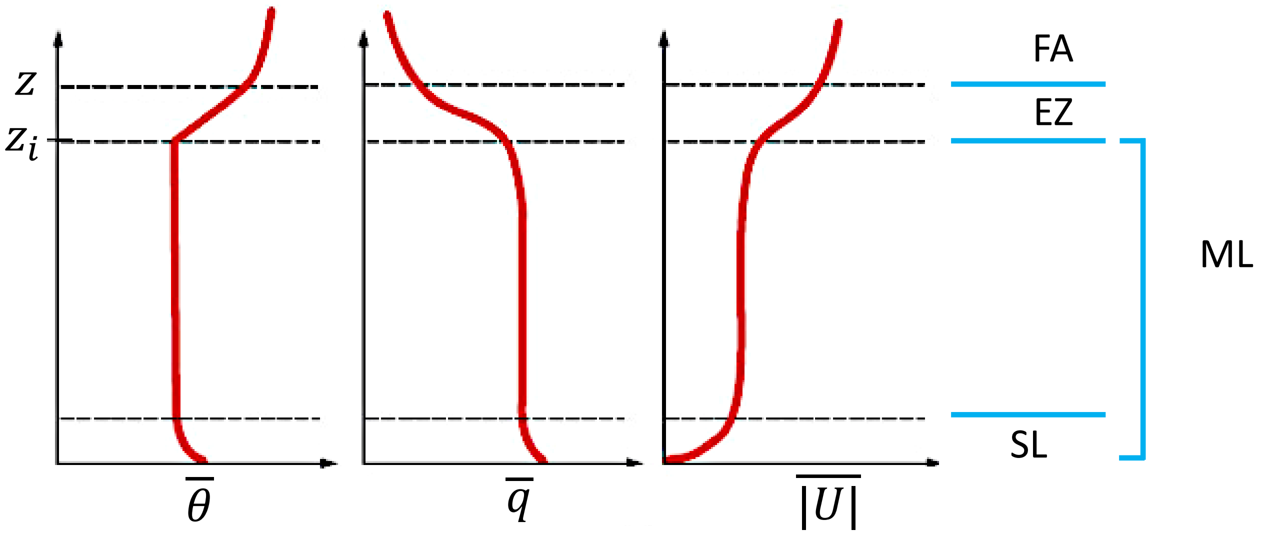


The entrainment of dry, cold air from the free atmosphere and environment can occur at the top of the PBL



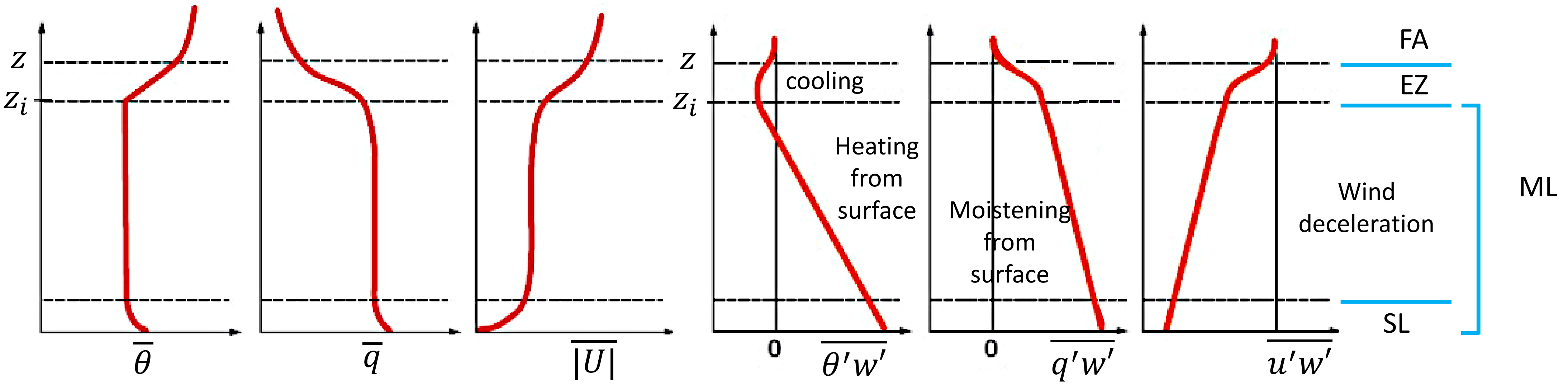
Diurnal cycle of PBL mean quantities and fluxes

Daytime



Diurnal cycle of PBL mean quantities and fluxes

Daytime



Unstable surface layer leads to convective heating from the surface

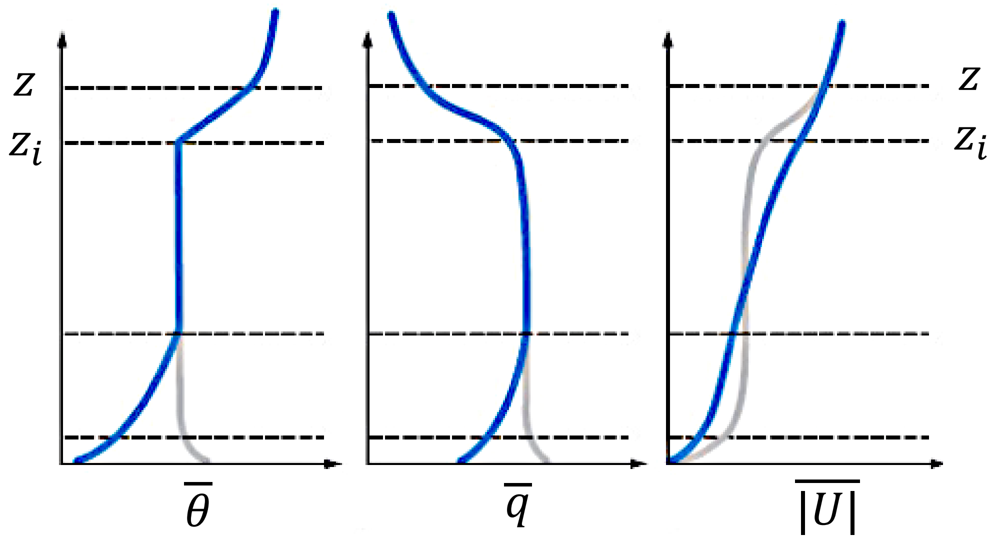
Leads to well mixed layer

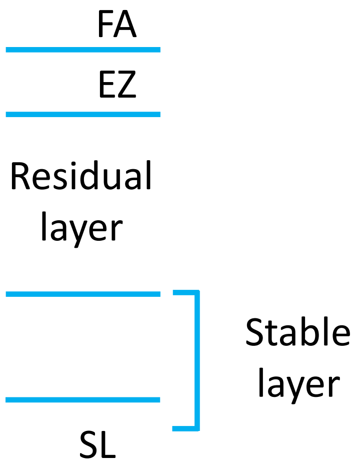
Entrainment from free atmosphere leads to cooling and drying at top of PBL

ECMWF

Diurnal cycle of PBL mean quantities and fluxes

Nighttime



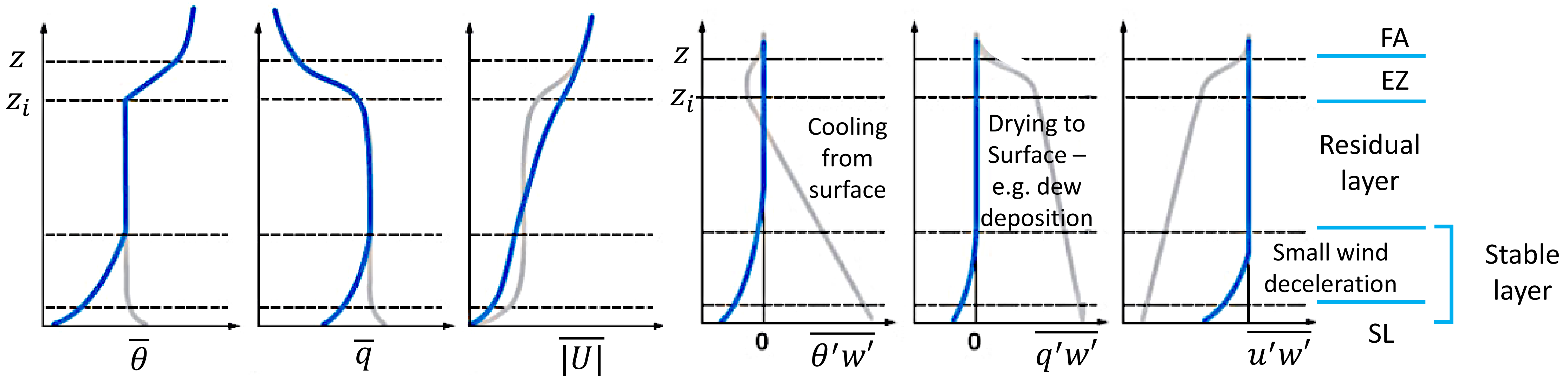


Stable surface layer develops due to cooling from the surface, inhibiting vertical mixing

Winds accelerate at the top of the PBL

Diurnal cycle of PBL mean quantities and fluxes

Nighttime



Stable surface layer develops due to cooling from the surface, inhibiting vertical mixing

Winds accelerate at the top of the PBL

Fluxes reduce as convective turbulence reduces - but can lead to very strong near surface gradients over shallow layers

Clear and cloudy convective boundary layers

ECMWF

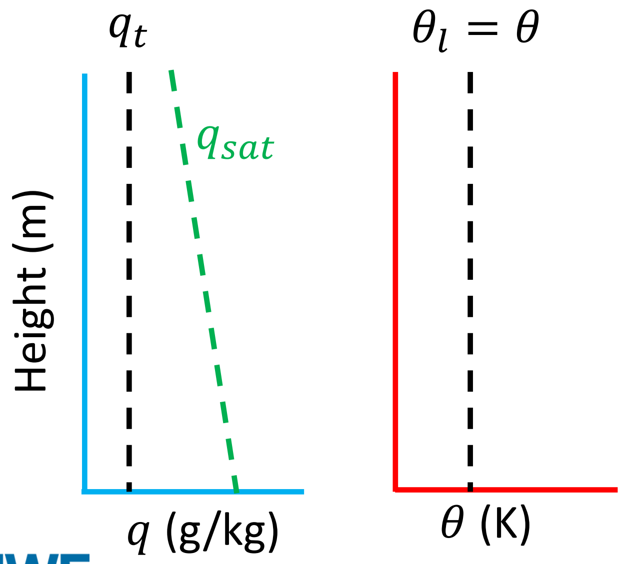
Clear convective boundary layer

Mixing is driven by:

- surface fluxes
- entrainment from environment

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

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



Cloudy convective boundary layer

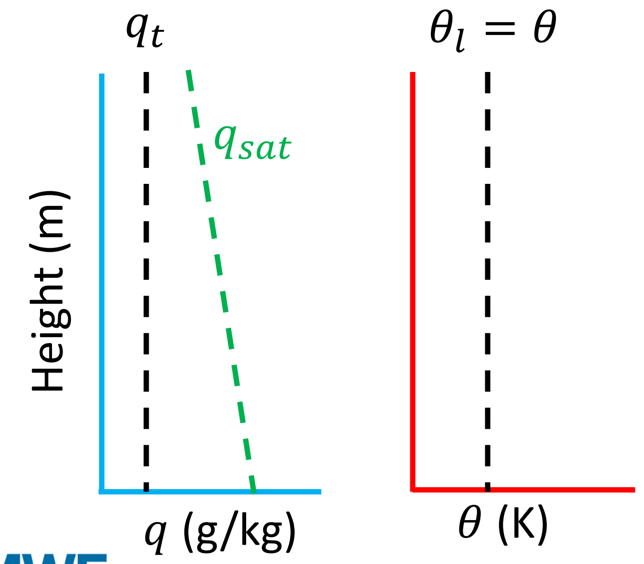
Clear convective boundary layer

Mixing is driven by:

- surface fluxes
- entrainment from environment

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

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



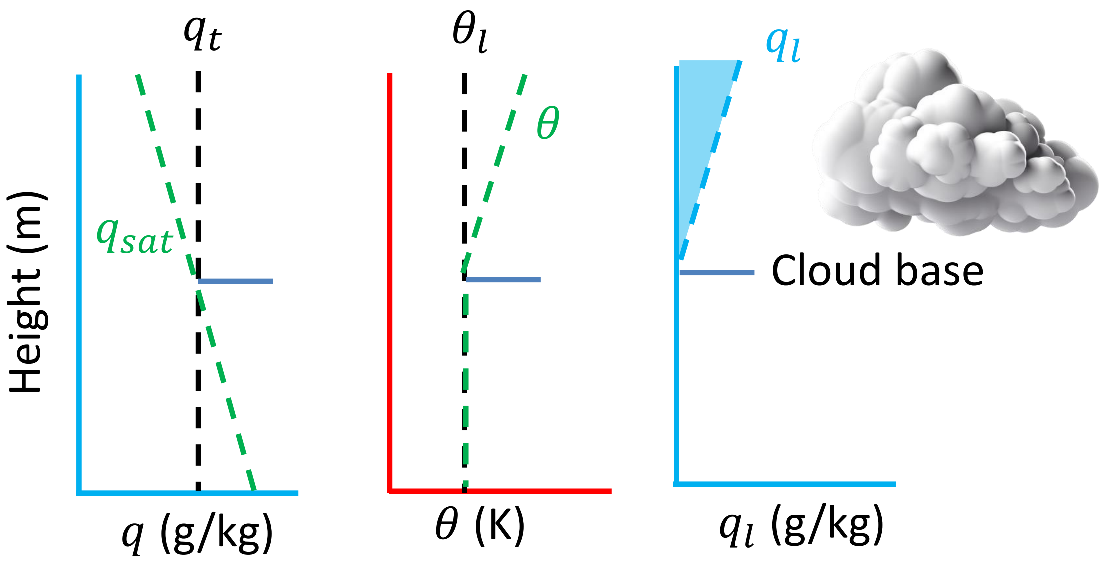
Cloudy convective boundary layer

Mixing is driven by:

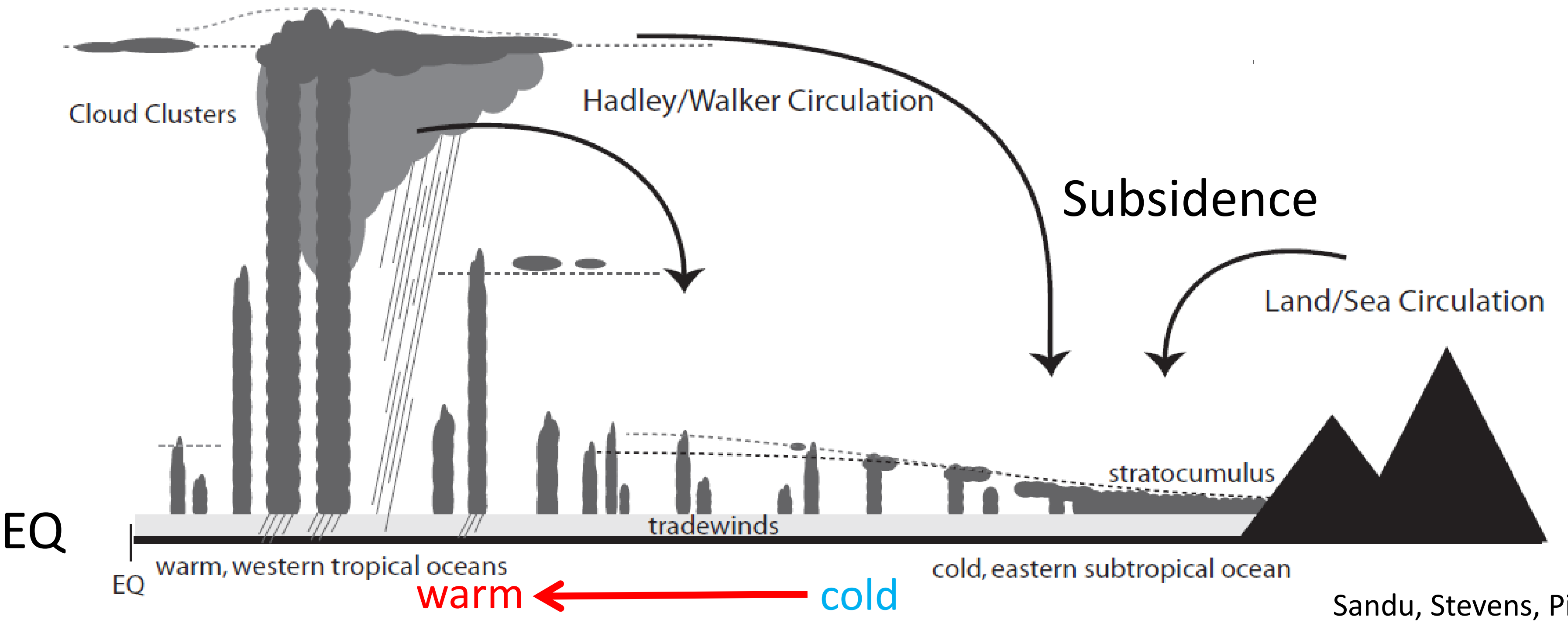
- surface fluxes
- cloud top eddies
- radiative heating / cooling
- entrainment from environment

Total water content $$q_t = q_v + q_l = \frac{m_v + m_l}{m_d + m_v + m_l}$$

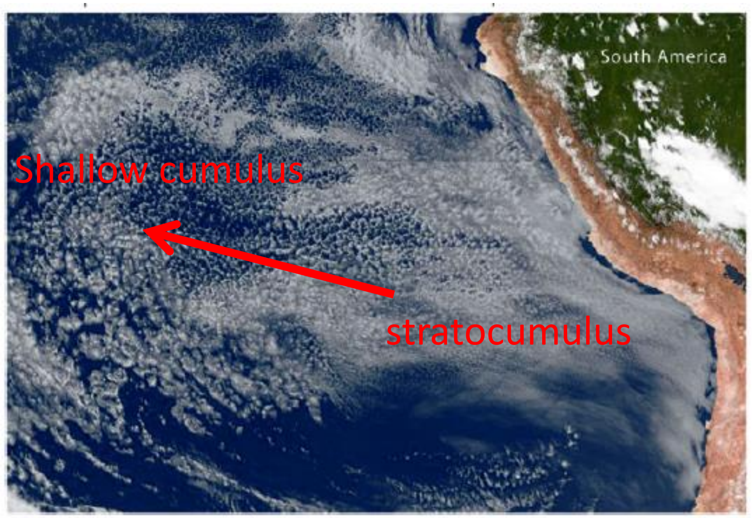
Liquid water potential temperature $$\theta_l = \theta - \frac{L_v}{c_p} q_l$$

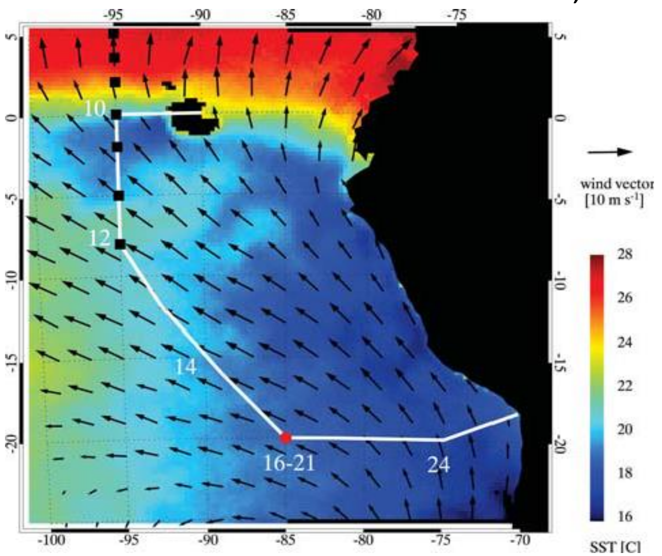


Development of clouds over sea surface



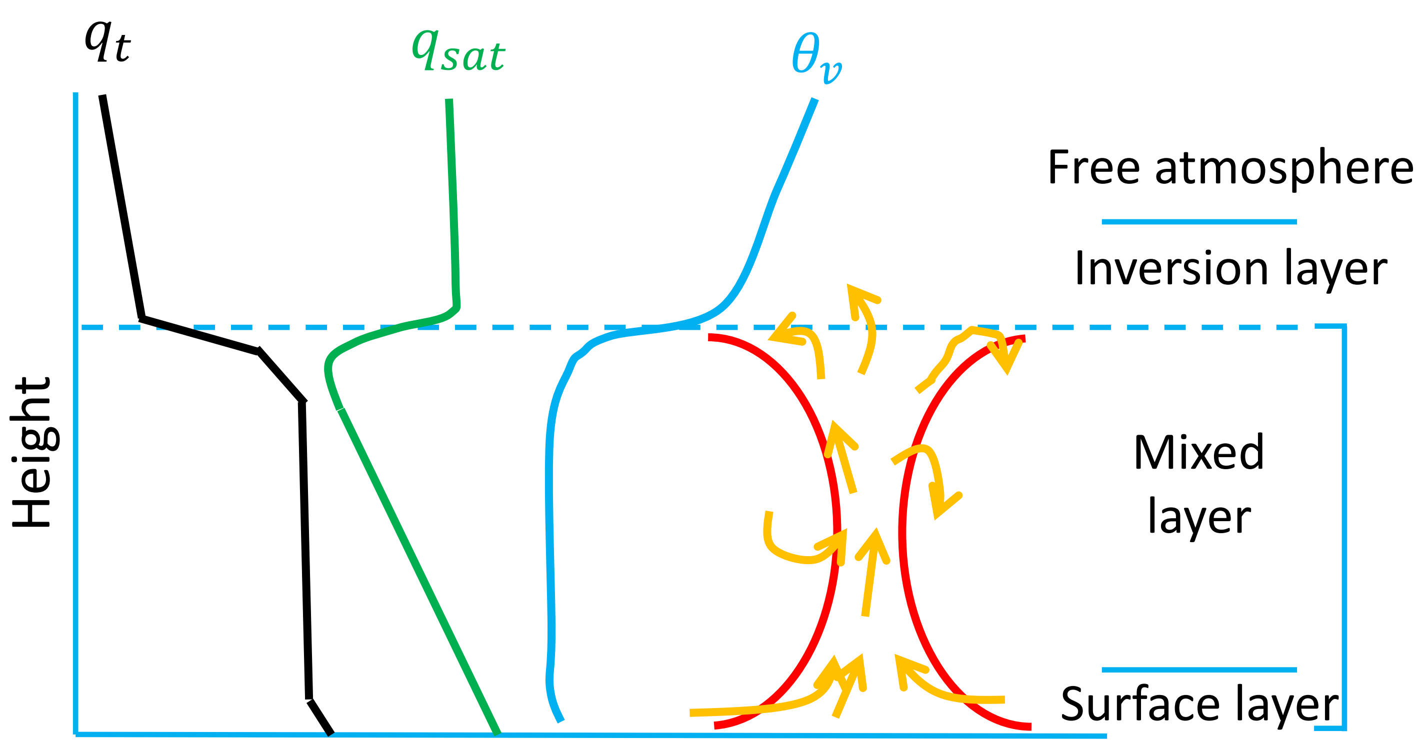
Sandu, Stevens, Pincus, 2010

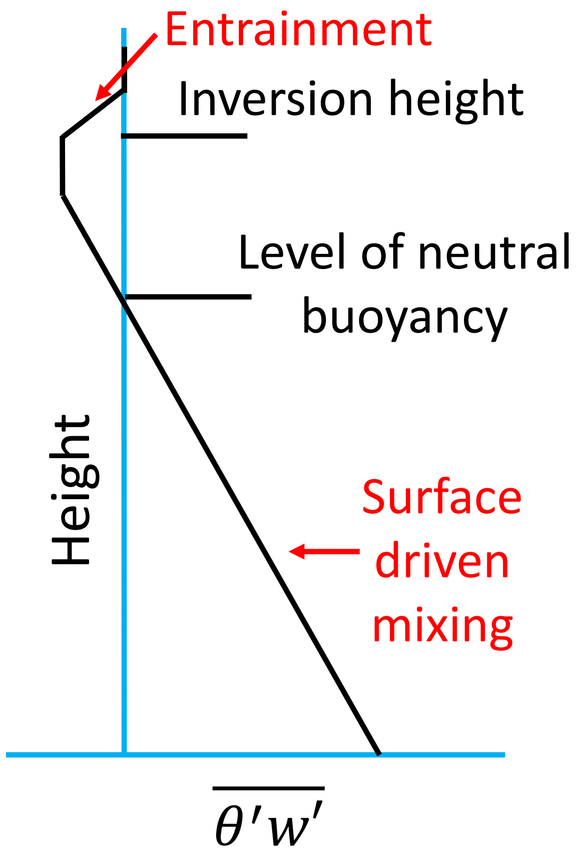




SST & surface wind

Mixing in clear convective PBLs



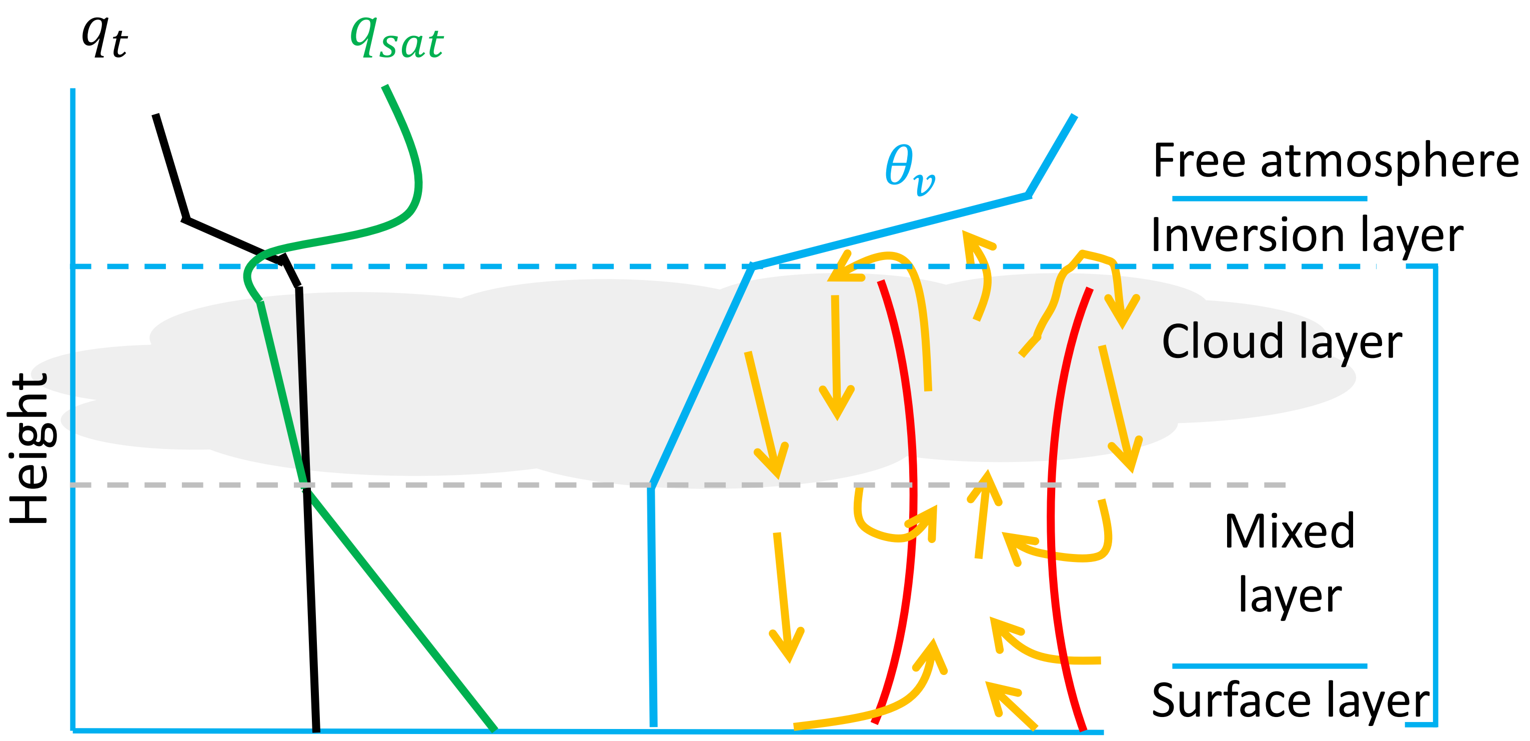


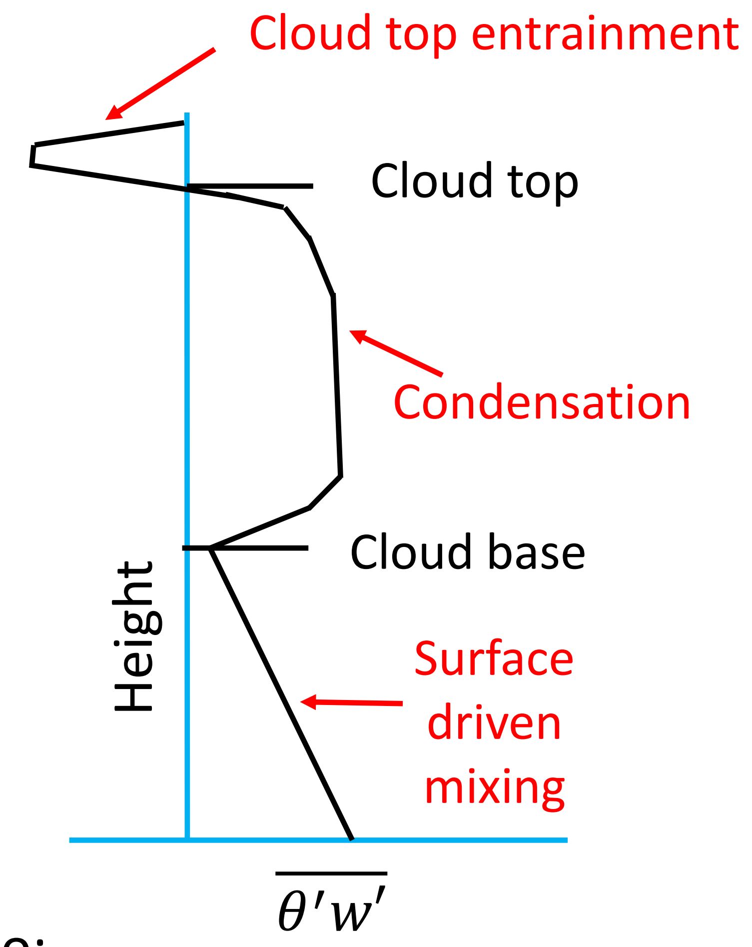
Mixing in clear convective boundary layers:

- Driven by surface convection
- Mixing occurs up to the inversion height
- Entrainment of environment air at top of PBL

Level of neutral buoyancy is point at which convection stops:
air parcel density == environment density

Mixing in stratoculums topped PBLs

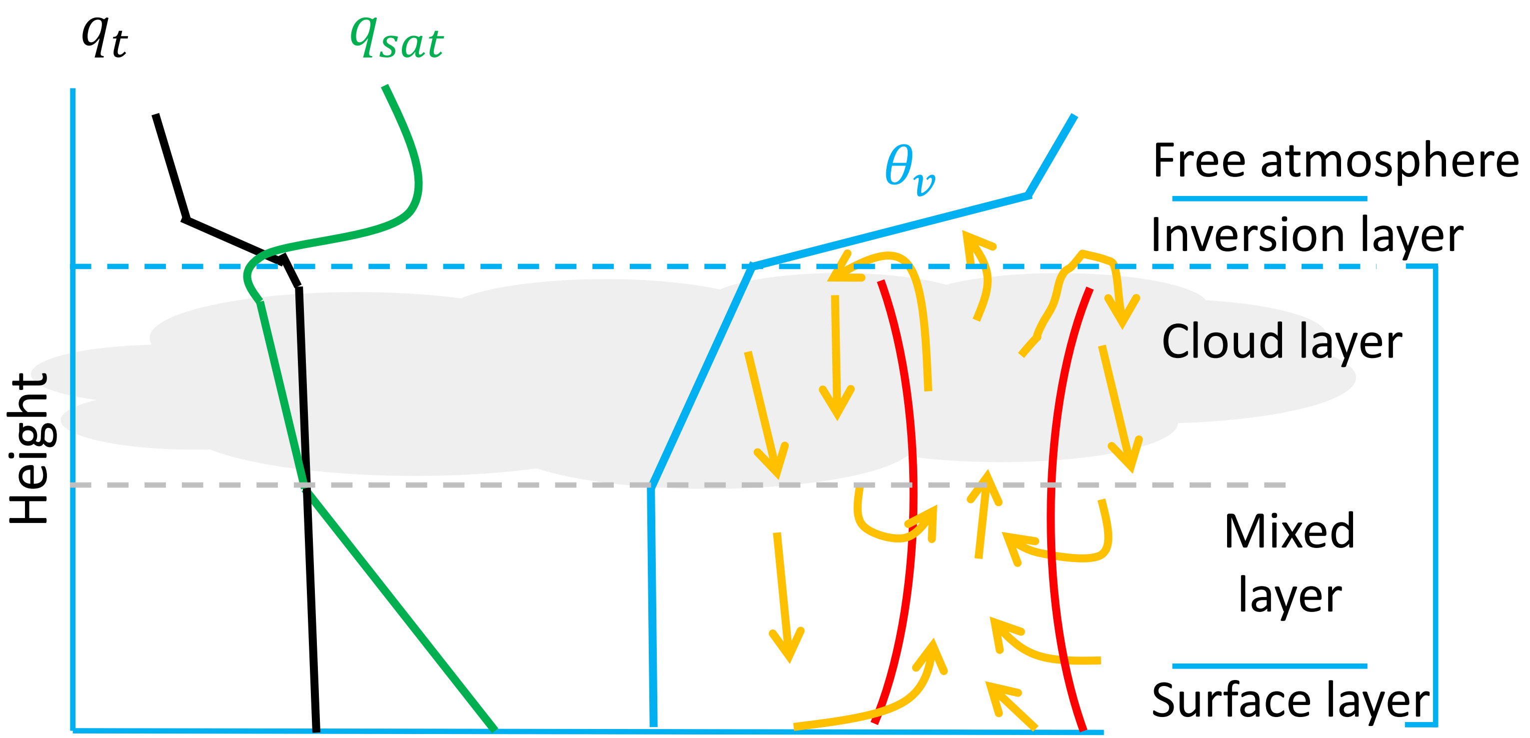


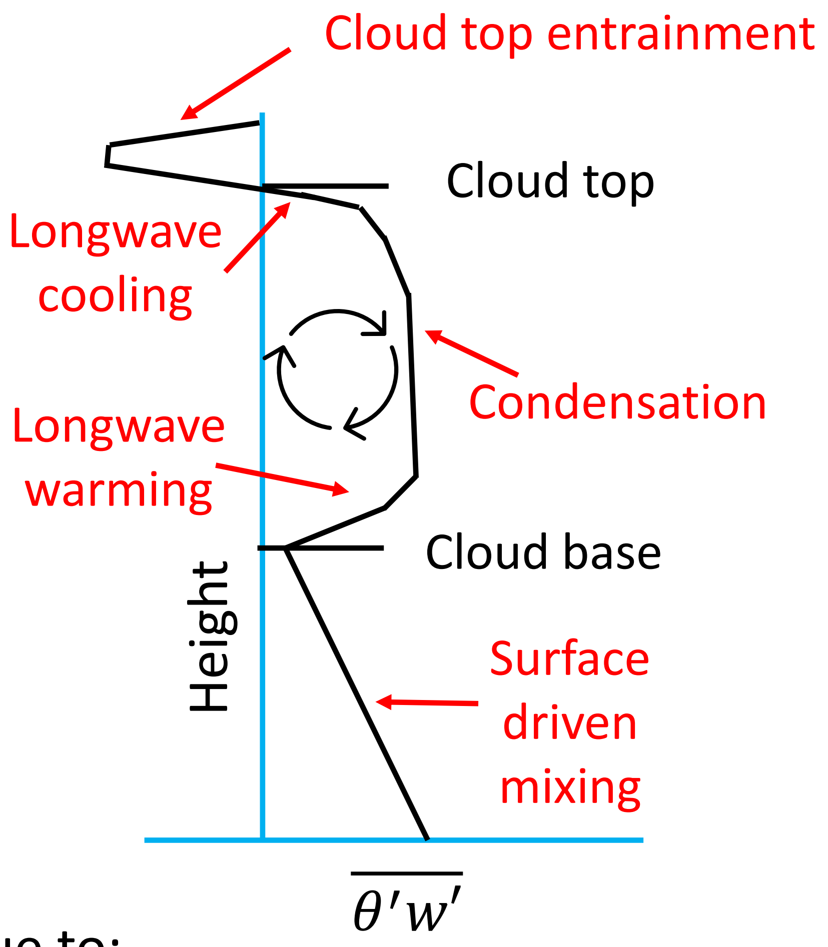


Mixing in stratocumulus clouds is more complex due to:

- Stronger entrainment from free atmosphere
- Condensation within cloud
- Radiative heating/cooling, which is essential for cloud evolution

Mixing in stratoculums topped PBLs





Mixing in stratocumulus clouds is more complex due to:

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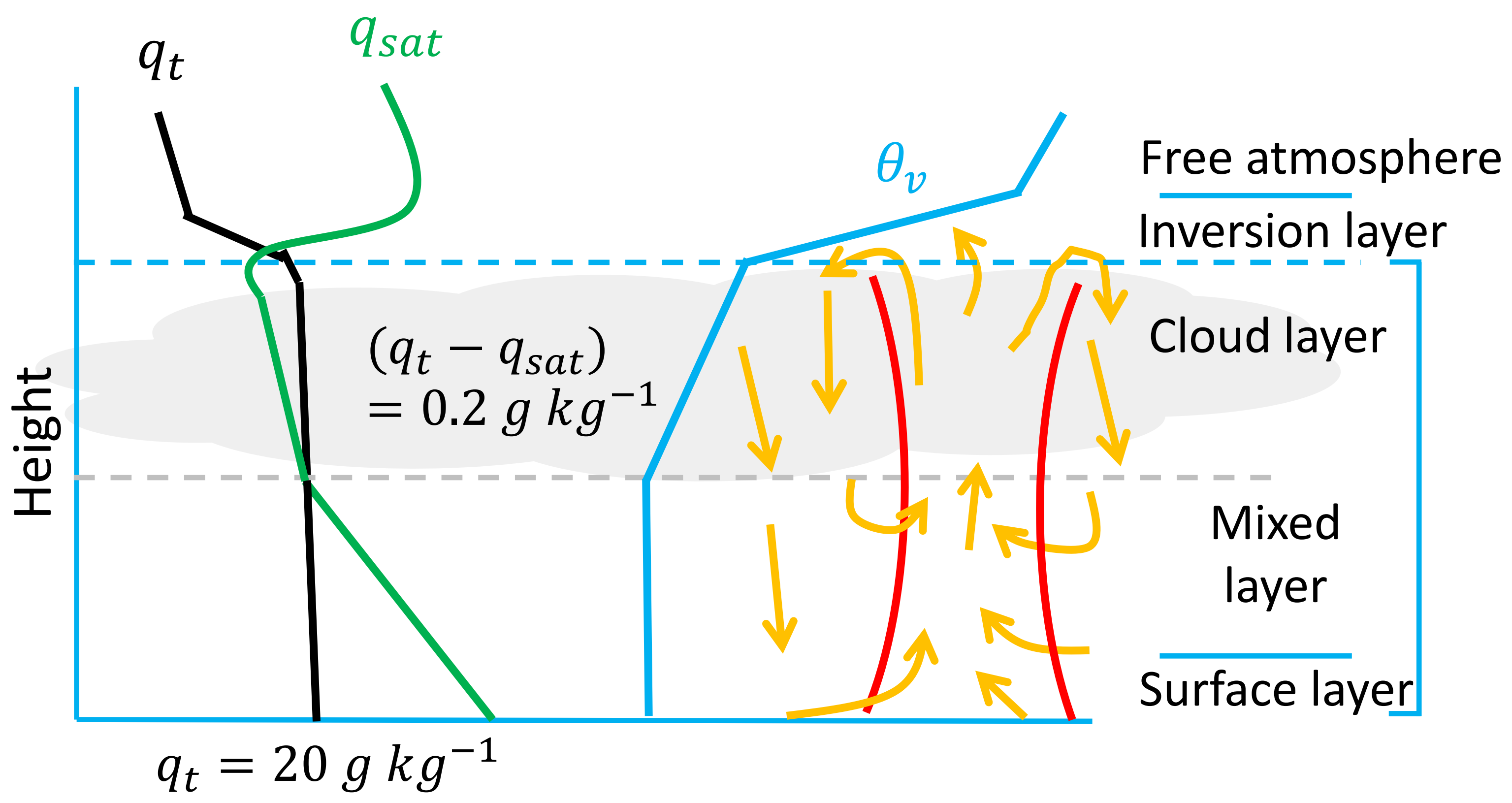
Stratoculums topped PBLs are very sensitive to mixing



The presence of stratocumulus is sensitive to:

Mixing in stratocumulus clouds is more complex due to:

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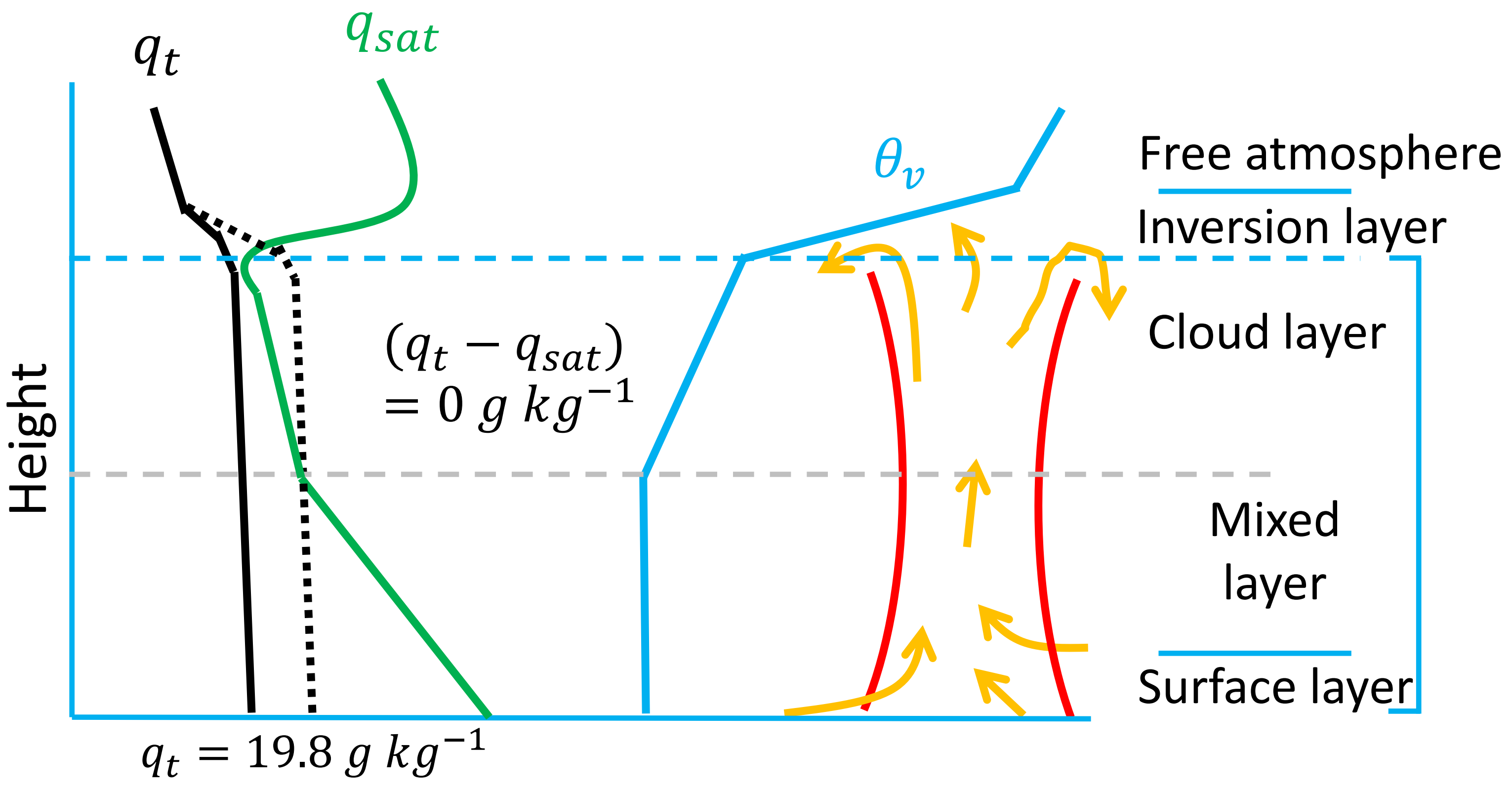
Stratoculums topped PBLs are very sensitive to mixing



The presence of stratocumulus is sensitive to:

- Small variations in humidity

Mixing in stratocumulus clouds is more complex due to:
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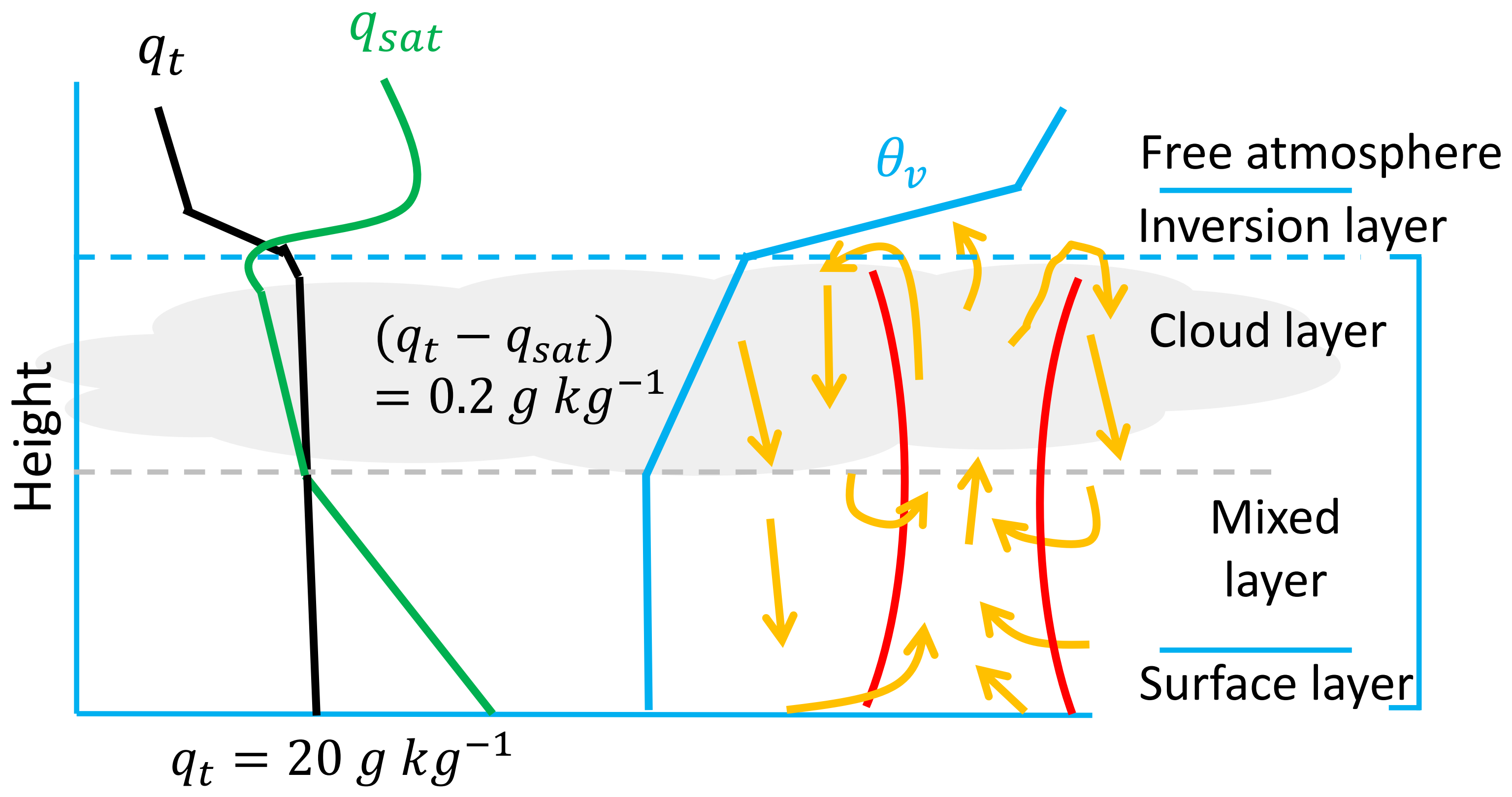
Stratoculums topped PBLs are very sensitive to mixing



The presence of stratocumulus is sensitive to:

- Small variations in humidity

- Small variations in temperature

Mixing in stratocumulus clouds is more complex due to:
- Stronger entrainment from free atmosphere
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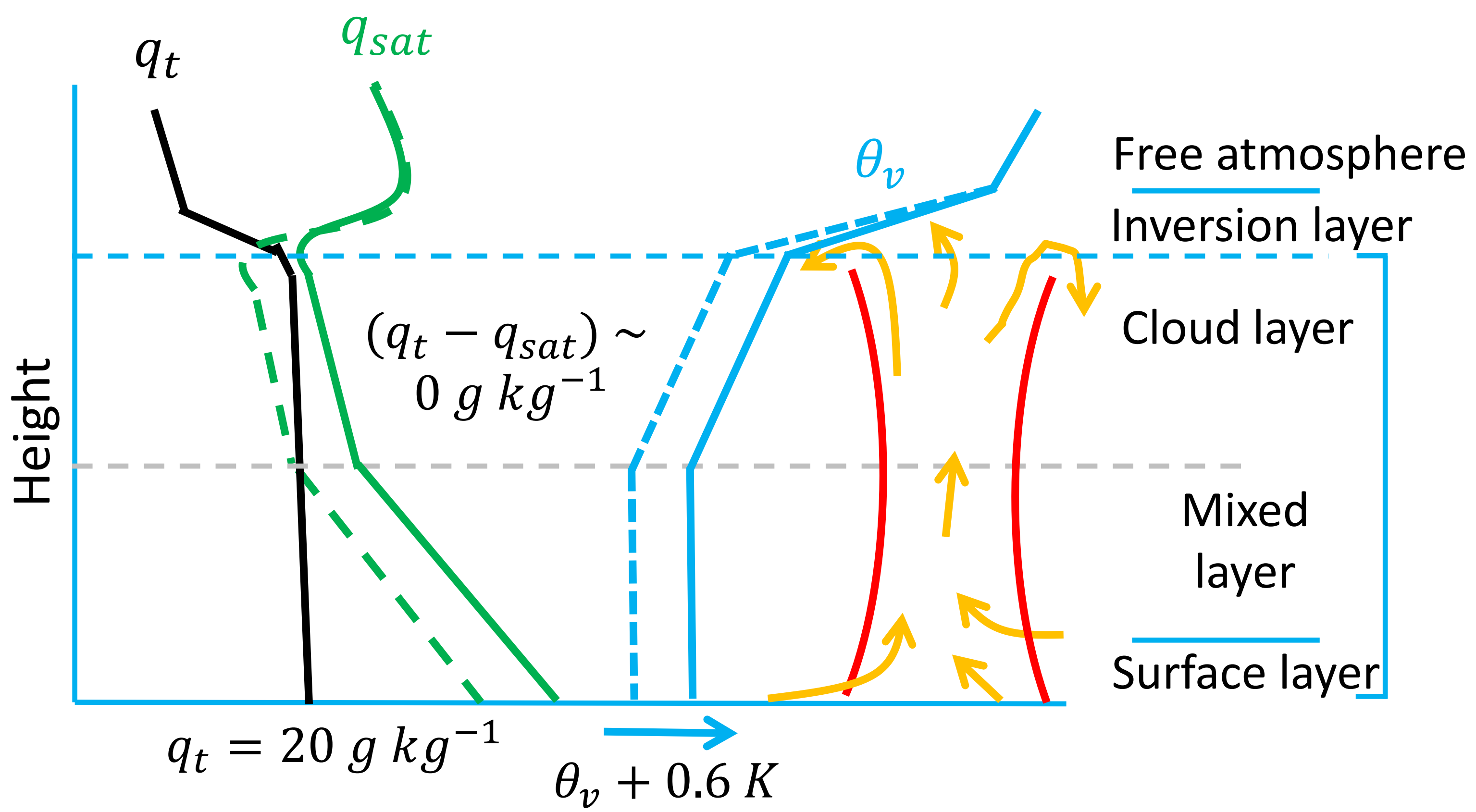
- Radiative heating/cooling, which is essential for cloud evolution

ECMWF

Stratoculums topped PBLs are very sensitive to mixing



The presence of stratocumulus is sensitive to:

- Small variations in humidity
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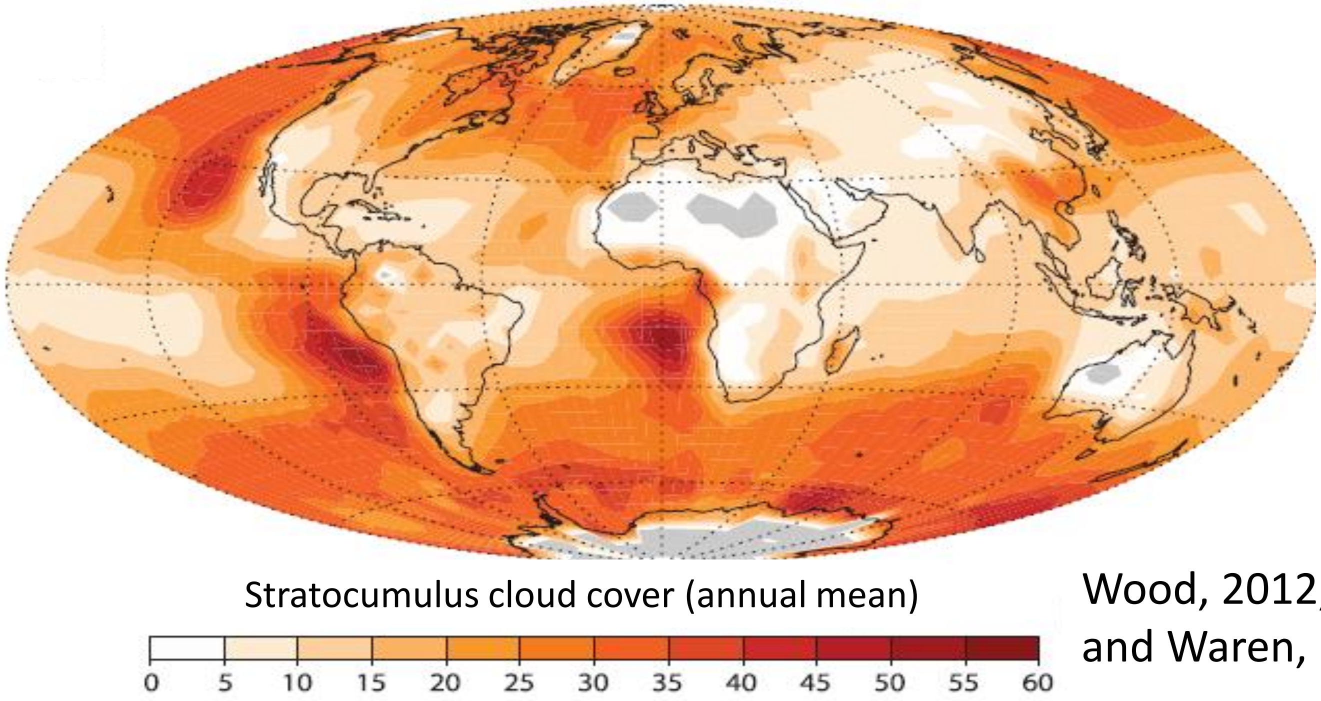
Mixing in stratocumulus clouds is more complex due to:

- Stronger entrainment from free atmosphere
- Condensation within cloud
- Radiative heating/cooling, which is essential for cloud evolution

Stratocumulus – Why are they important?

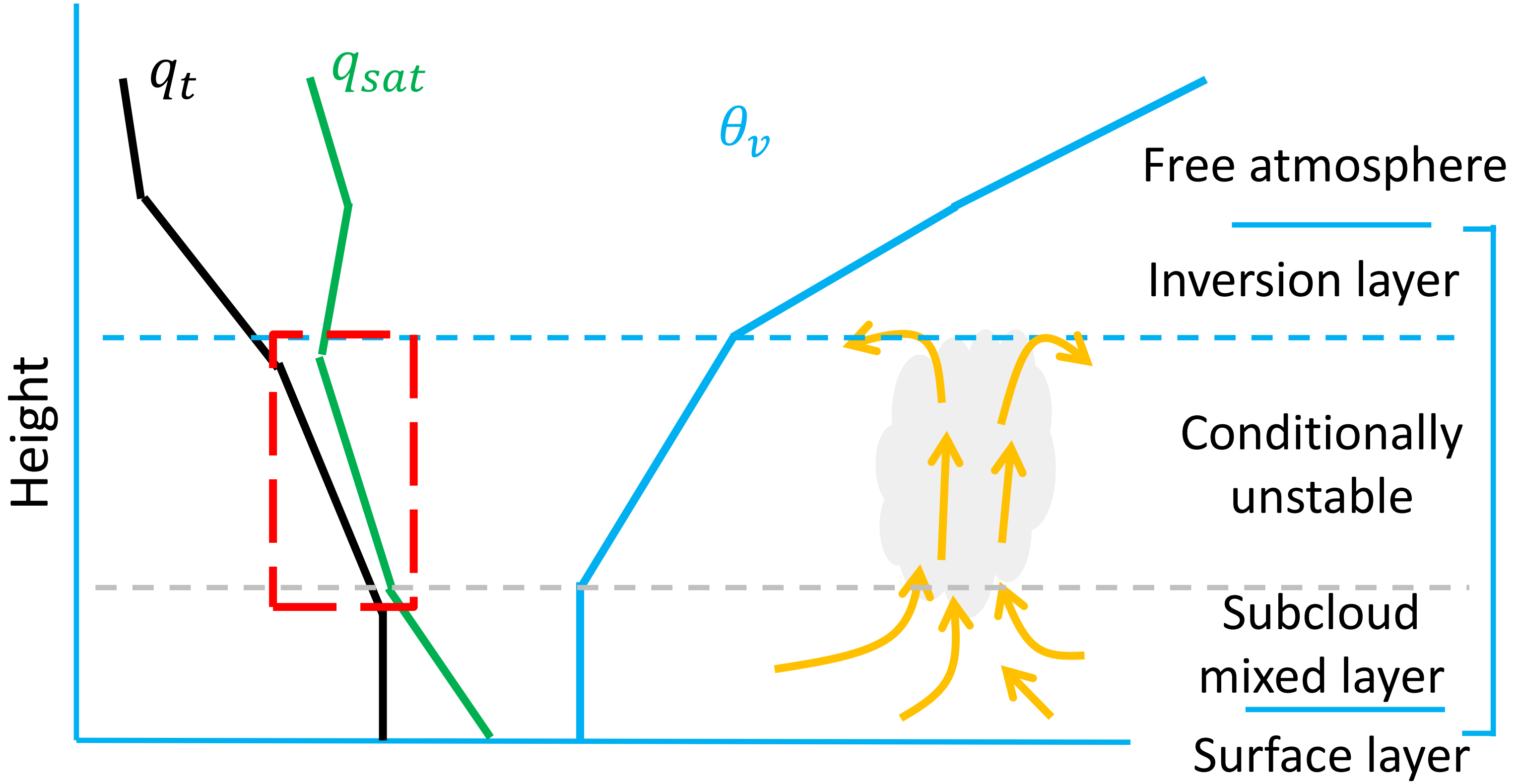
- They cover on (annual) average 29% of the planet (Klein and Hartmann, 1993)
- Cloud top albedo is 50-80% (in contrast to 7 % at ocean surface)
- Increase in global stratocumulus extent could offset several degrees of global warming (Randall et al. 1984)
- Coupled models have large biases in stratocumulus extent and SST

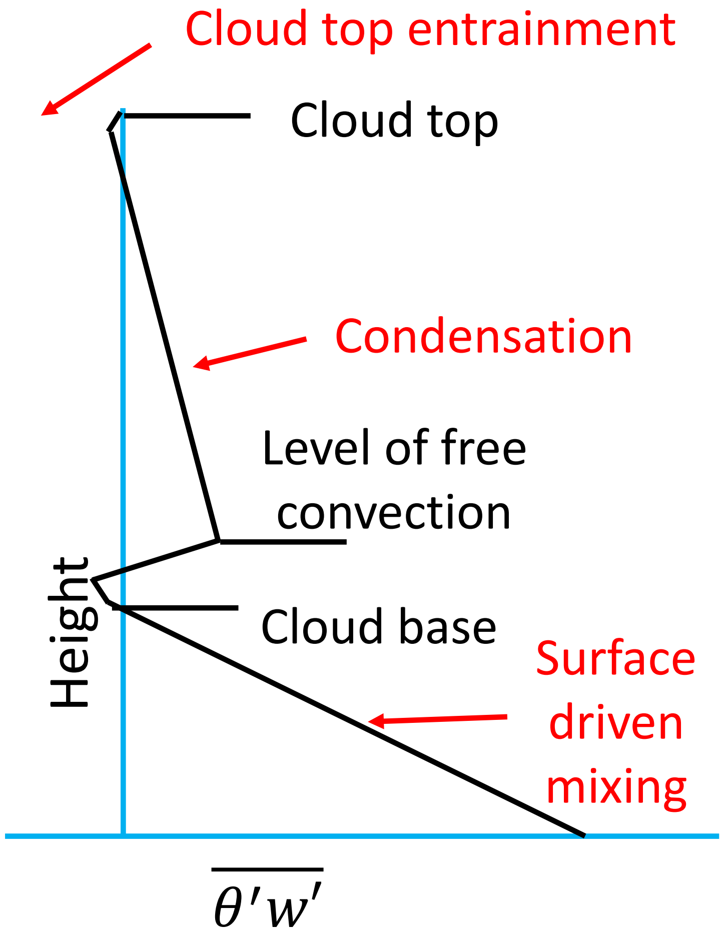


Stratocumulus cloud cover (annual mean)

Wood, 2012,based on Han and Waren, 2007

Mixing in cumulus topped PBLs





Mixing in cumulus clouds:

- Mean specific humidity is below saturation ($q_t < q_{sat}$), because of small area fraction
- Very strong surface driven mixing – represented by mass flux scheme (see later)
- Inertia of parcel causes it to continue rising, reaching level of free convection

ECMWF

Summary of PBL and turbulence

- **The PBL is:**
  - Directly influenced by the presence of the Earth's surface through turbulent exchange of momentum, heat and moisture
- **Types of tubulence:**
  - Shear and convective
  - Their relative influence is measured by Richardson number, $Ri = \frac{N^2}{\left(\frac{dU}{dz}\right)^2}$
- **Reynolds decomposition is used to:**
  - Separate the (large-scale) mean fluxes from the (small-scale) turbulent fluxes
  - Show that vertical divergence of turbulent fluxes impact large scale mean flow (e.g. heating)
- **Diurnal cycle of PBL:**
  - Near-surface stability (Richard number) and turbulent fluxes change throughout the day
  - Diurnal cycle much stronger over land than over ocean
- **Cloudy PBL:**
  - Presence of cloud changes nature of turbulent mixing due to entrainment and radiation