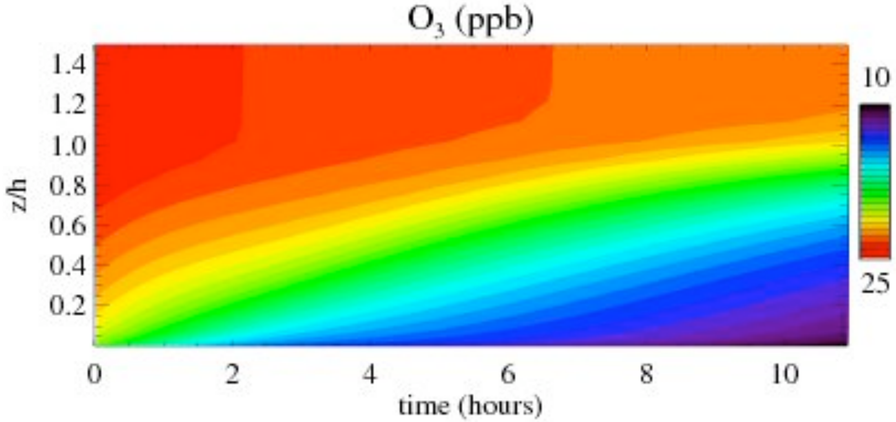
Turbulent dispersion and chemical transformation in the atmospheric boundary layer:

Part II: Clouds and stable stratification

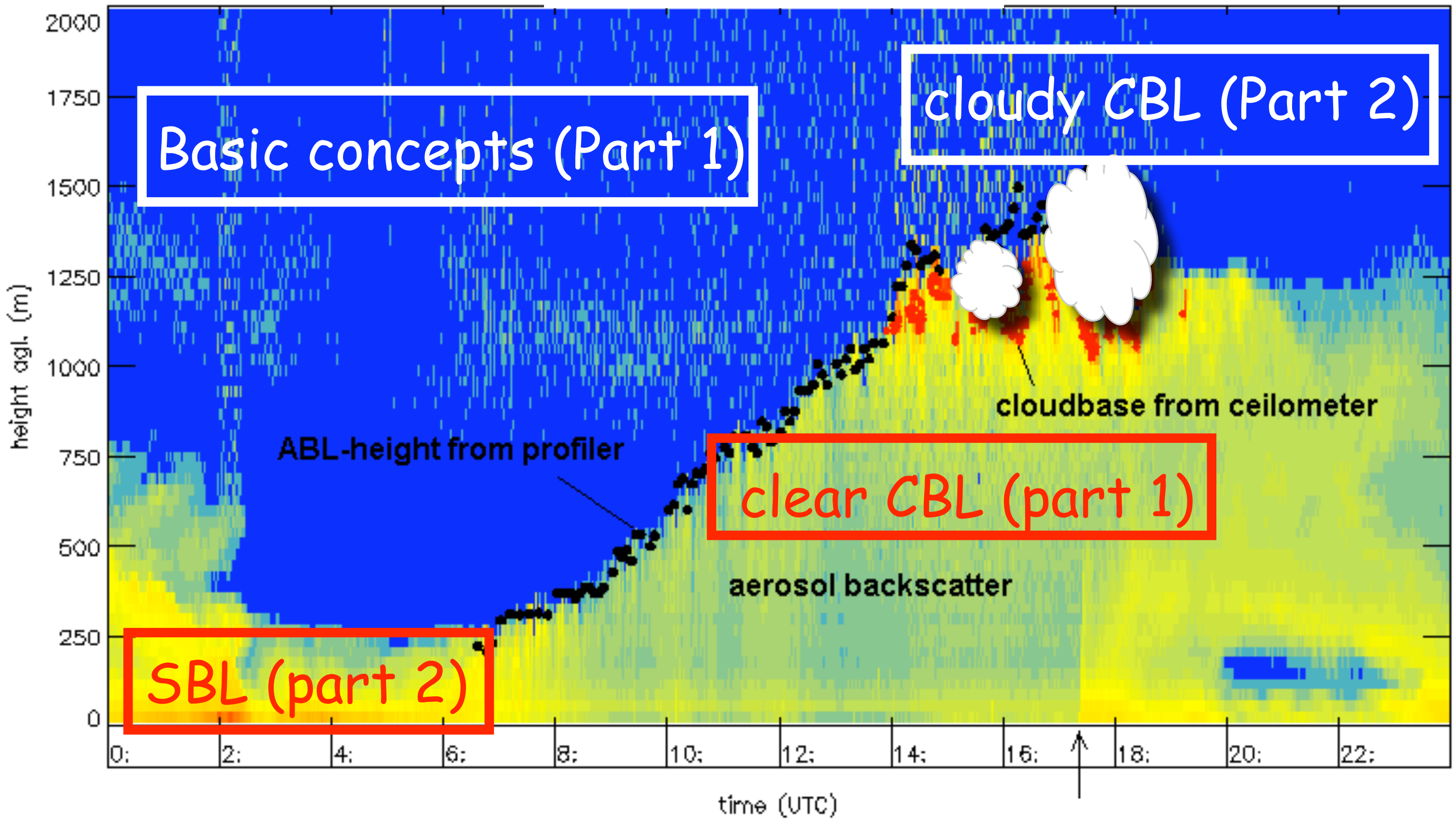


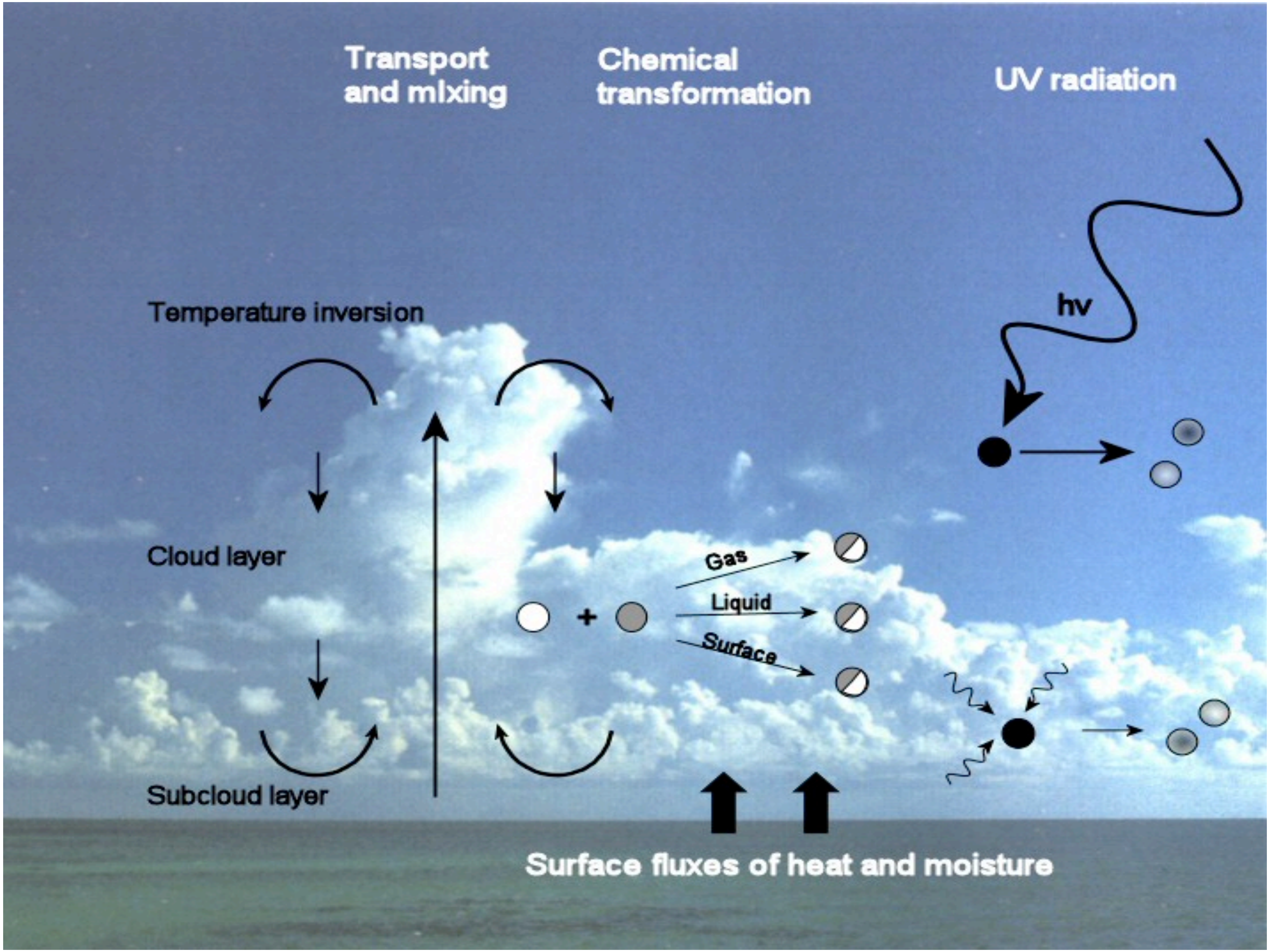
Jordi Vilà-Guerau de Arellano

WAGENINGEN UNIVERSITY
METEOROLOGY AND AIR QUALITY

Thanks: Remco Verzijlbergh
Thijs Heus/ Harm Jonker
Domenico Anfossi/S. Galmarini
Larry Mahrt

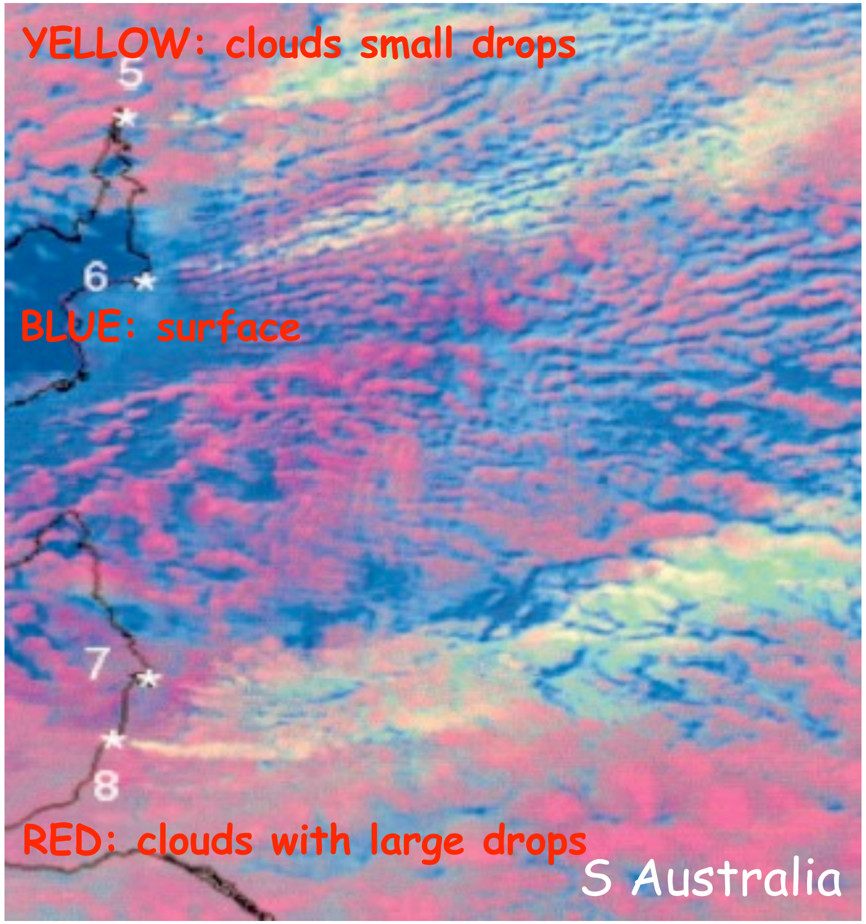
Organization of the 2 lectures




Transport
and mixing
Chemical
transformation
UV radiation
Temperature inversion
hv
Cloud layer
Gas
Liquid
Surface
Subcloud layer
Surface fluxes of heat and moisture

Why are we interested?

Interaction between boundary layer clouds and air pollution near sources



Processes

-Dynamics
-Turbulent dispersion
-Radiation
-Microphysics
-Chemistry

AVHRR (effective radius)
(Rosenfeld, 2000)

Cloudy Boundary Layer

-Refreshing main characteristics cloudy BL

- Dispersion (LAGRANGIAN)

Properties

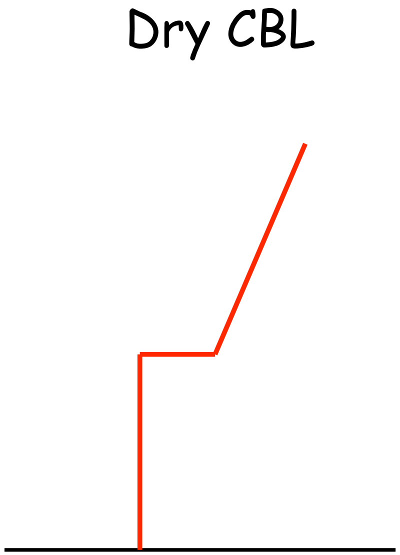
Vertical transport

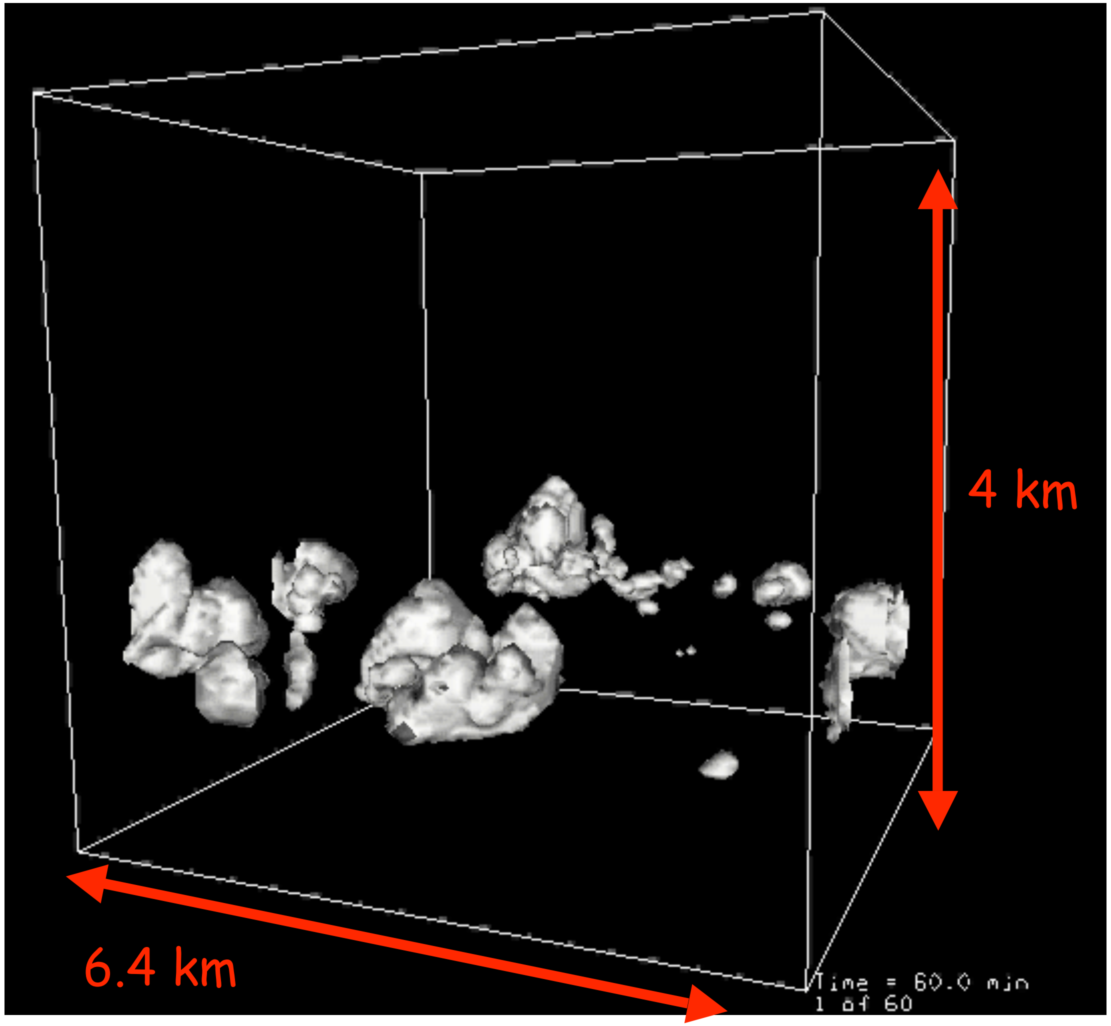
-Reactivity (EULERIAN)

Vertical transport/Ventilation

UV radiation

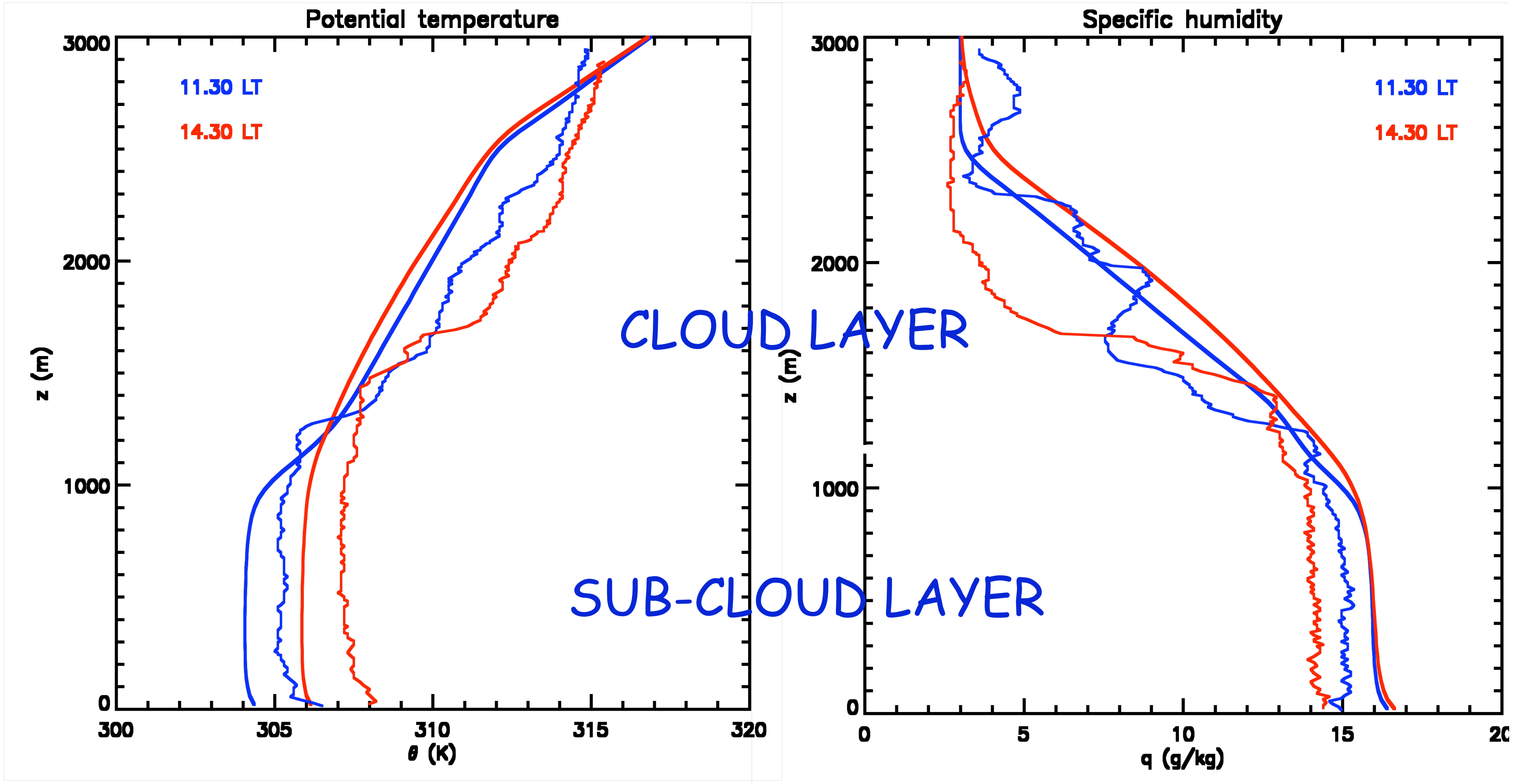
Cloudy boundary layer sketch



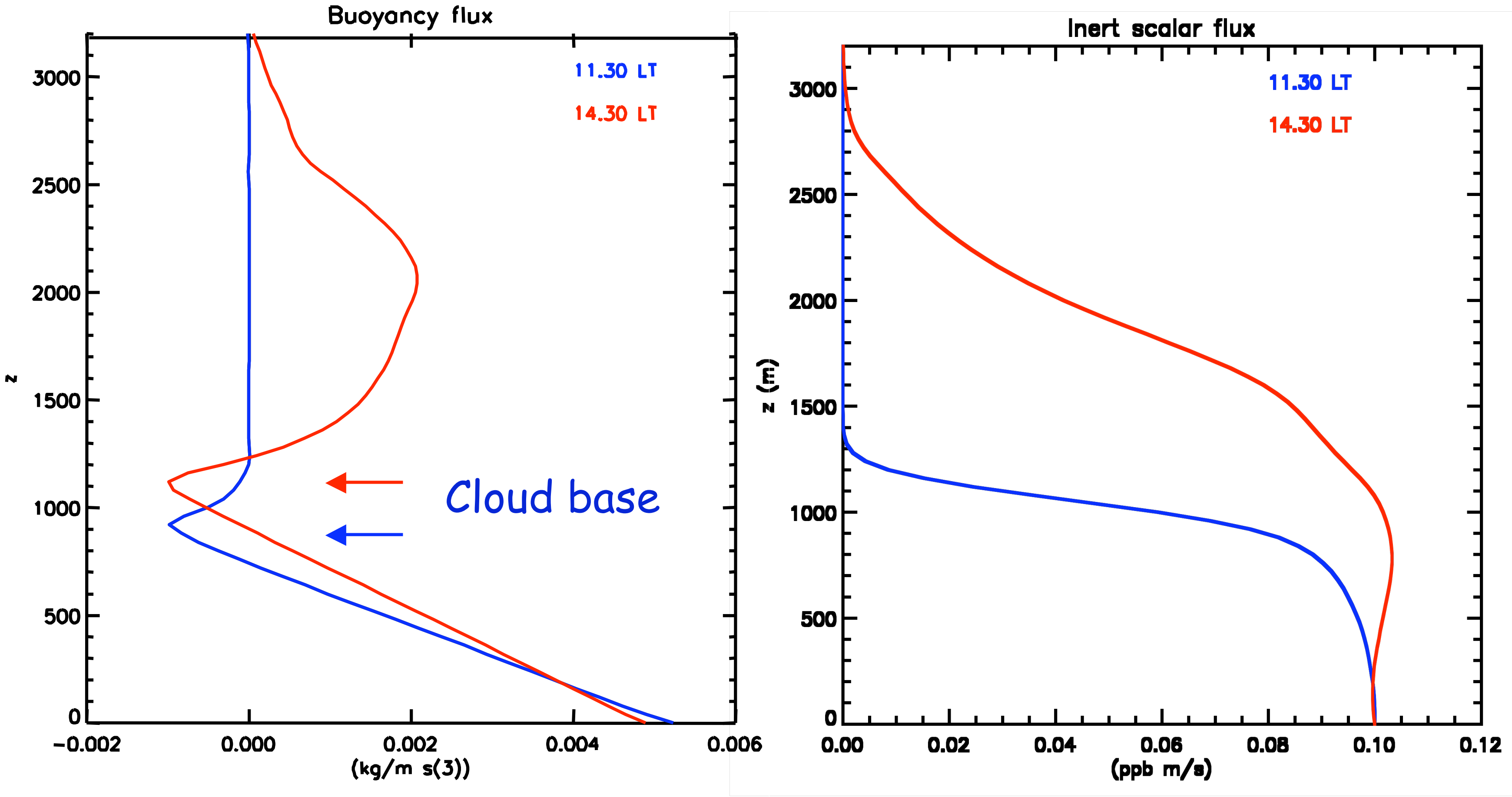

4 km
6.4 km
Time = 60.0 min
1 of 60

Vertical profiles

LES results (1-hour average) versus radisounding observations



Vertical profile buoyancy and scalar flux



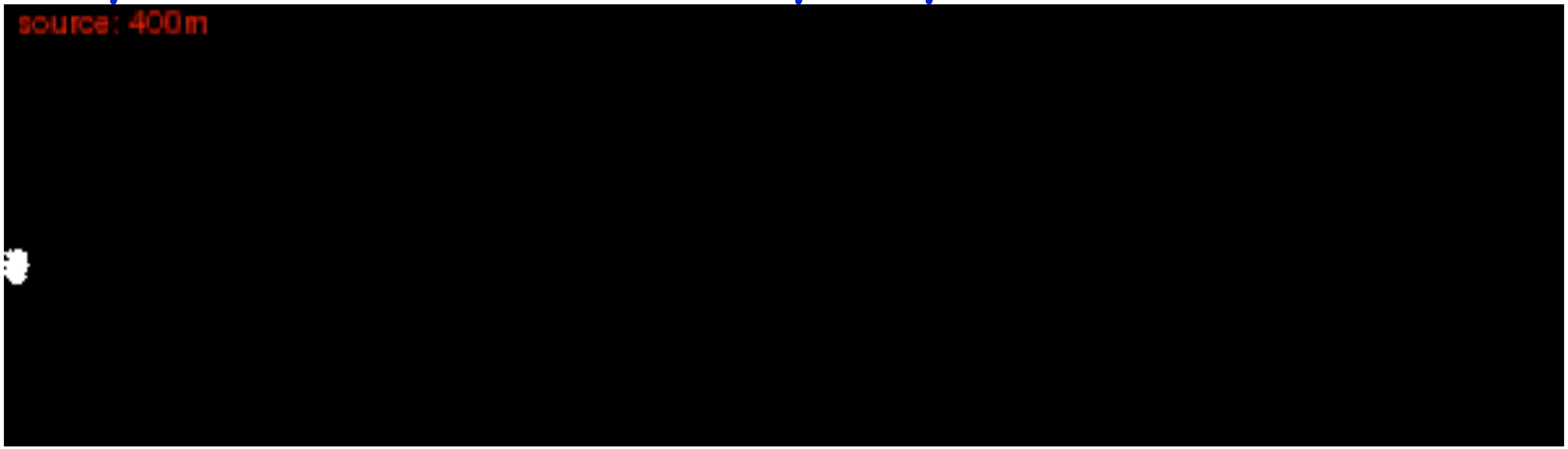
Turbulent dispersion in cloudy boundary layers

- Sub-cloud layer

- Cloud layer

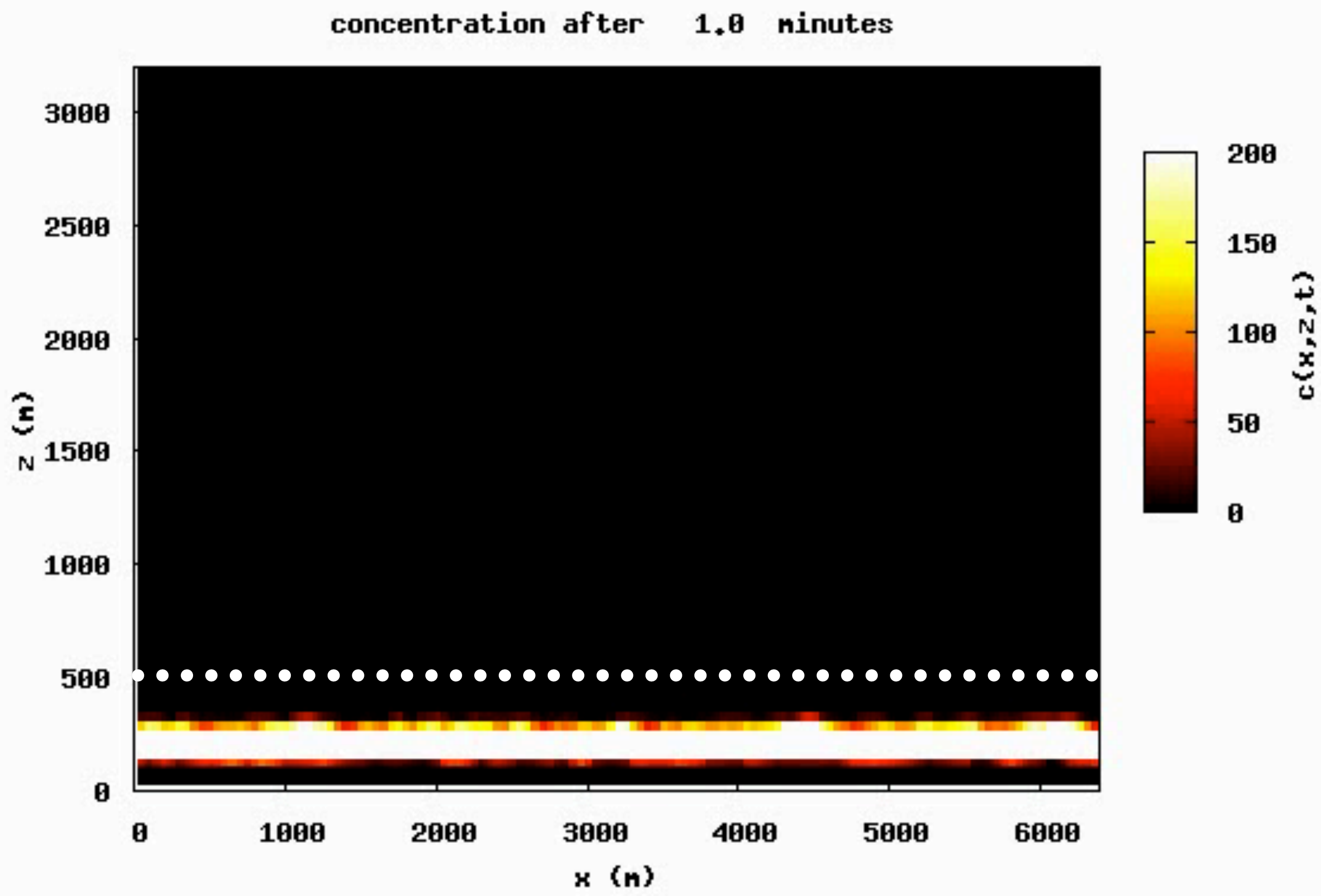
Dispersion of mass less particles. LES simulation with a Lagrangian particle model (including sub-grid model)

Dry Convective Boundary Layer (h=750 m)

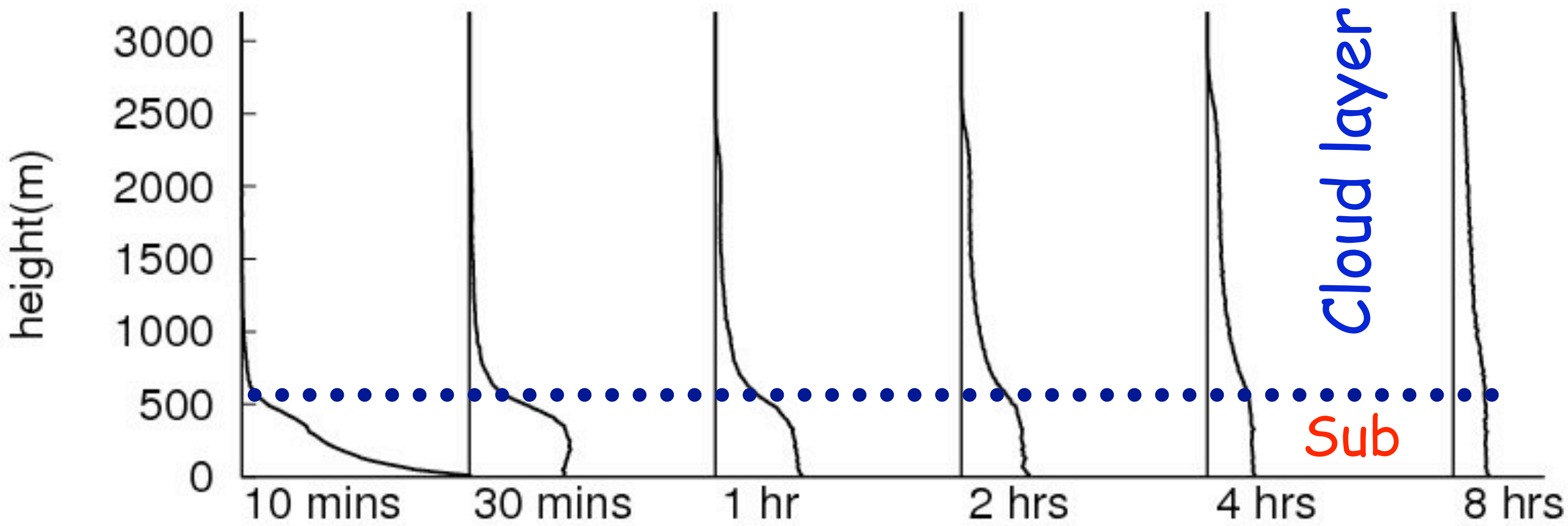


Particles are effectively mixed in the whole ABL

(Verzijlbergh et al., 2008)


concentration after 1.0 minutes
3000
2500
2000
1500
1000
500
0
z (m)
0
1000
2000
3000
4000
5000
6000
x (m)
200
150
100
50
0
c(x,z,t)

Emission released in the sub-cloud layer: similar as in the clear CBL

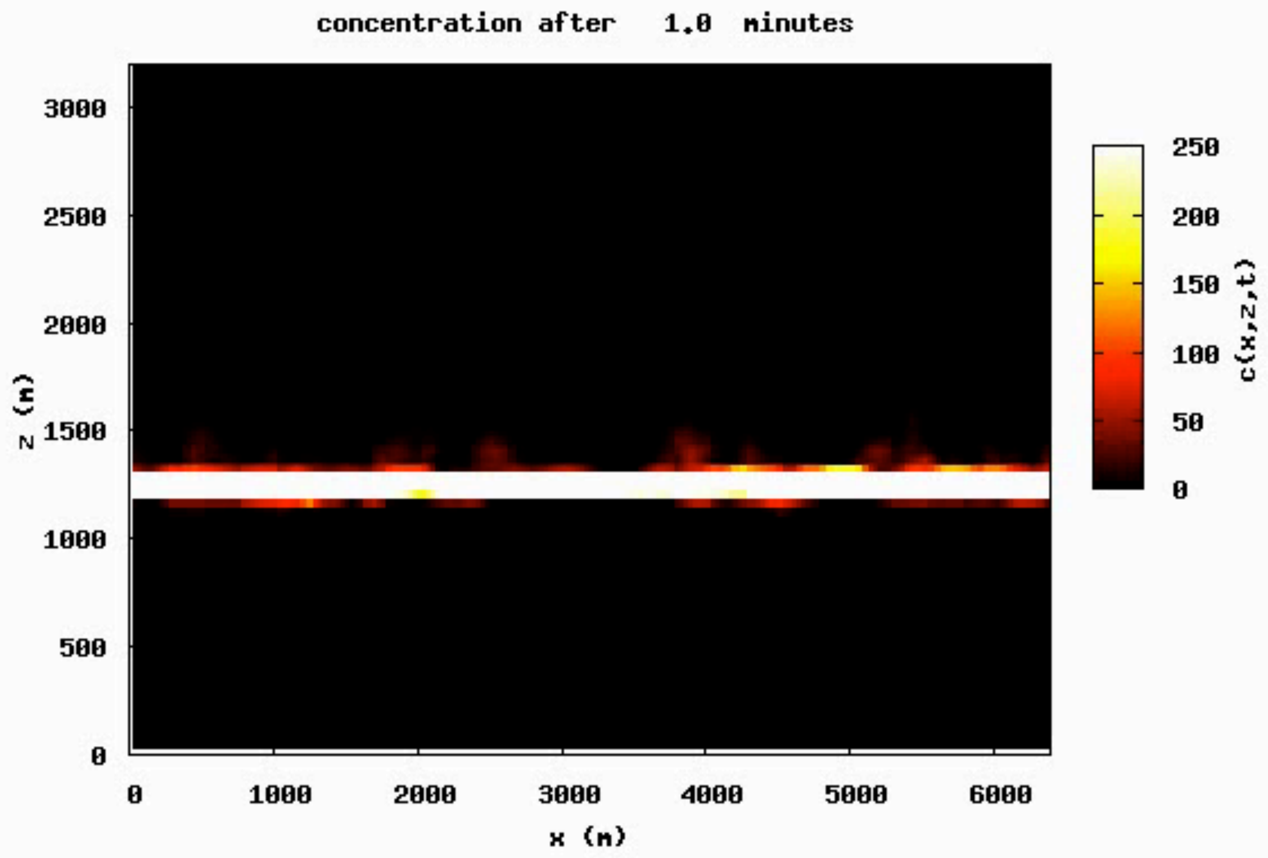


(Verzijlbergh et al., 2008)

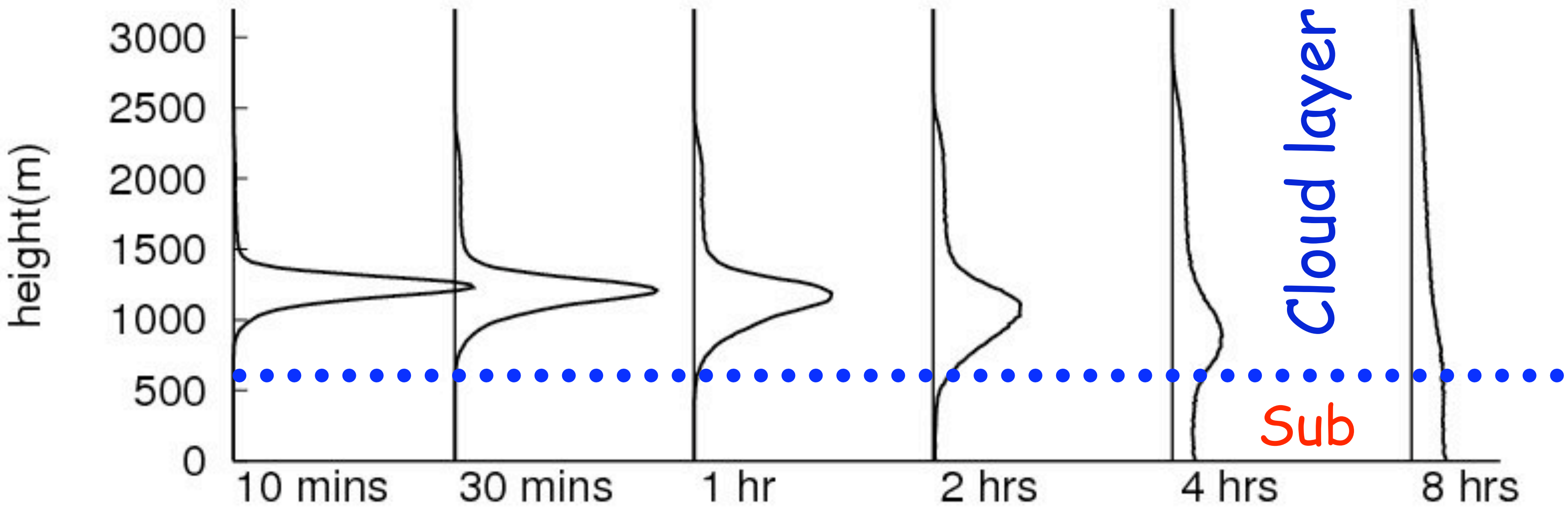
Dispersion in cloudy boundary layers

Particle are released in the cloud layer

Once the particles are introduced in
the cloud boundary layer, they remain there


concentration after 1.0 minutes
z (m)
x (m)
c(x,z,t)
0
500
1000
1500
2000
2500
3000
0
1000
2000
3000
4000
5000
6000
0
50
100
150
200
250

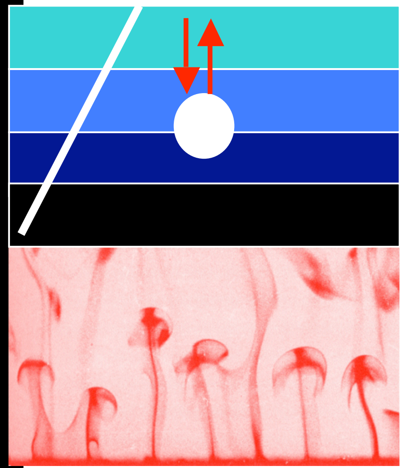
Emission released in the cloud layer



Dispersion properties cloudy BL

$$\frac{\partial \overline{\theta}}{\partial z}$$

Gravity force acts as a restoring force for displaced fluid elements

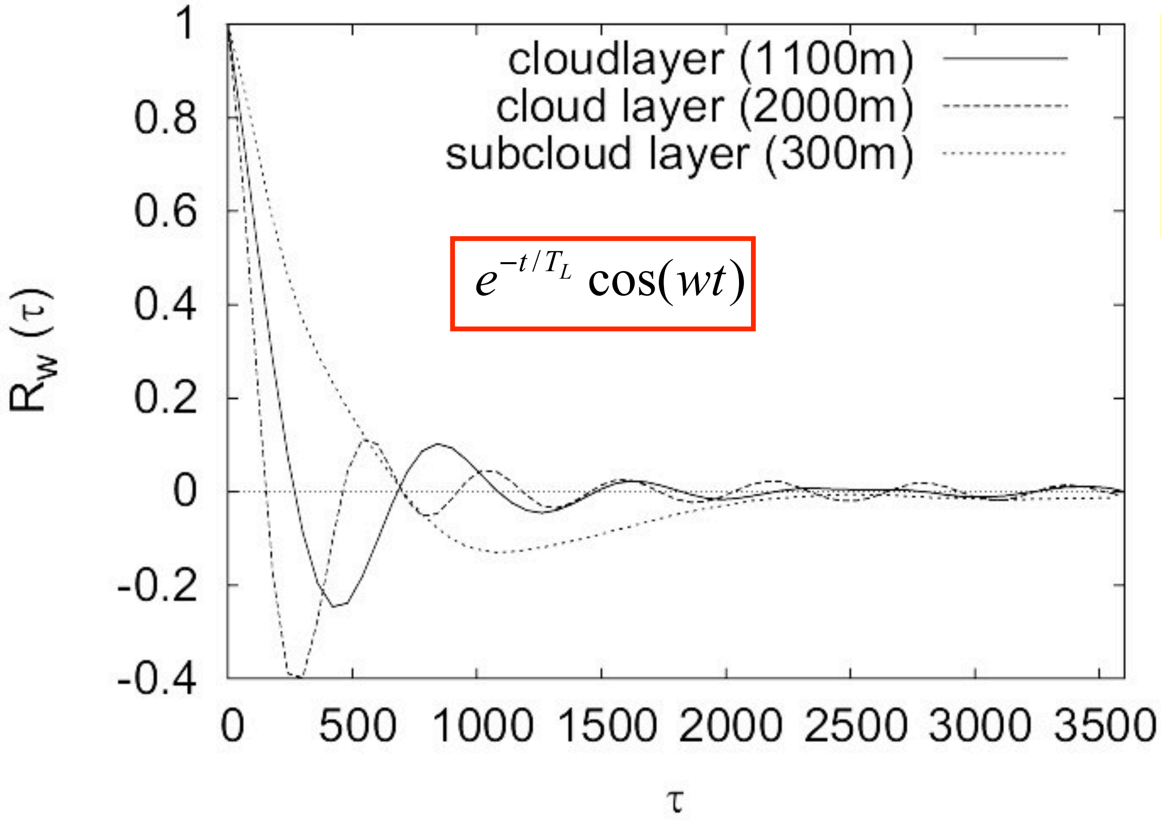


Cloud layer

Cloud venting

Sub-cloud layer

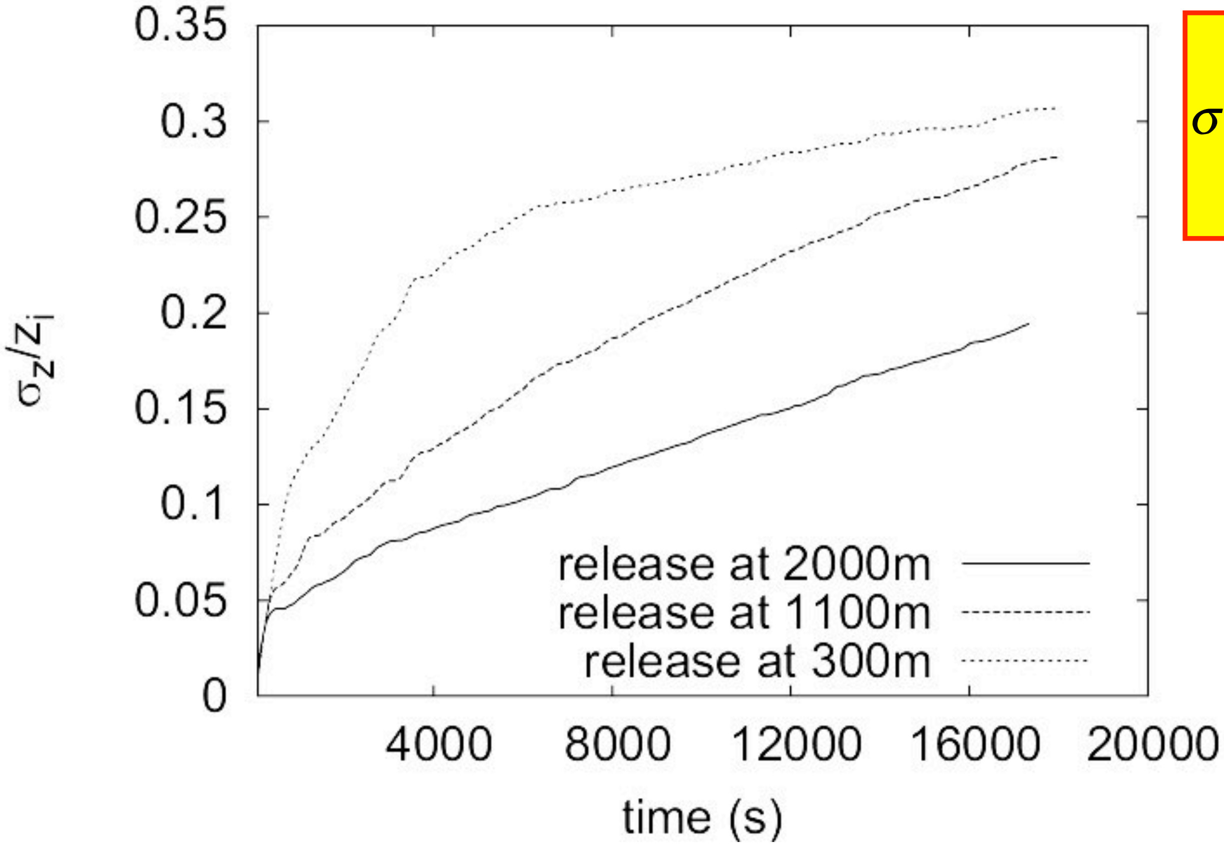
Autocorrelation vertical velocity



$$\sigma_j^{\,2}(T) = 2\overline{u_j^{\,2}}\int_o^T dt \int_o^t R_j(\tau)\,d\tau$$

(Verzijlbergh et al., 2008)

Vertical dispersion (z-comp)



$$\sigma_j^{\,2}(T) = 2\overline{u_j^{\,2}} \int_o^T dt \int_o^t R_j(\tau)\, d\tau$$

(Verzijlbergh et al., 2008)

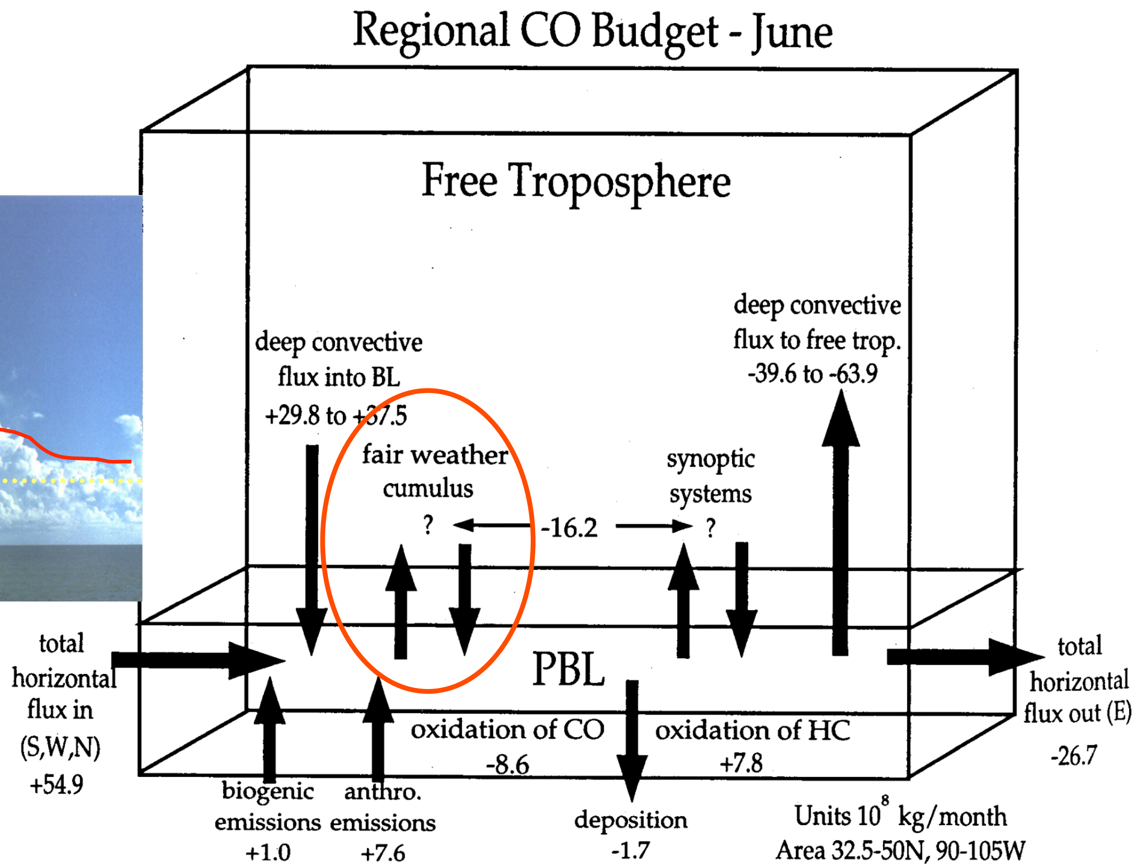
What about vertical transport and reactivity?

Increasing volume dilution (partially higher boundary layer)

Enhancement vertical transport by cloud ventilation

Perturbation of chemical equilibrium by physical processes:

Transport of reactants by shallow cumulus



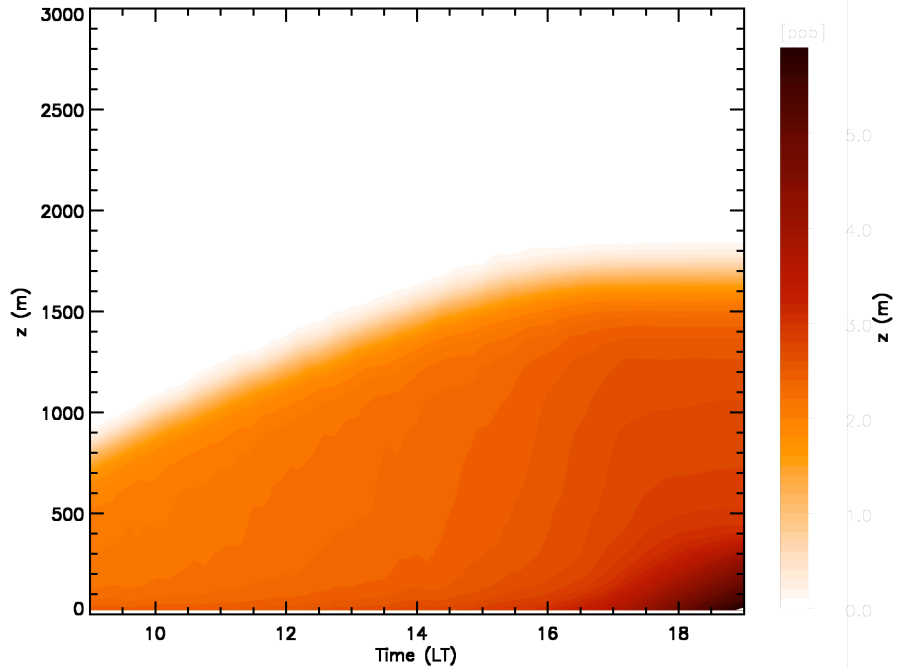
(Thompson et al., 1994)

What is the difference in the temporal evolution of the vertical distribution of a scalar with and without shallow cumulus clouds?

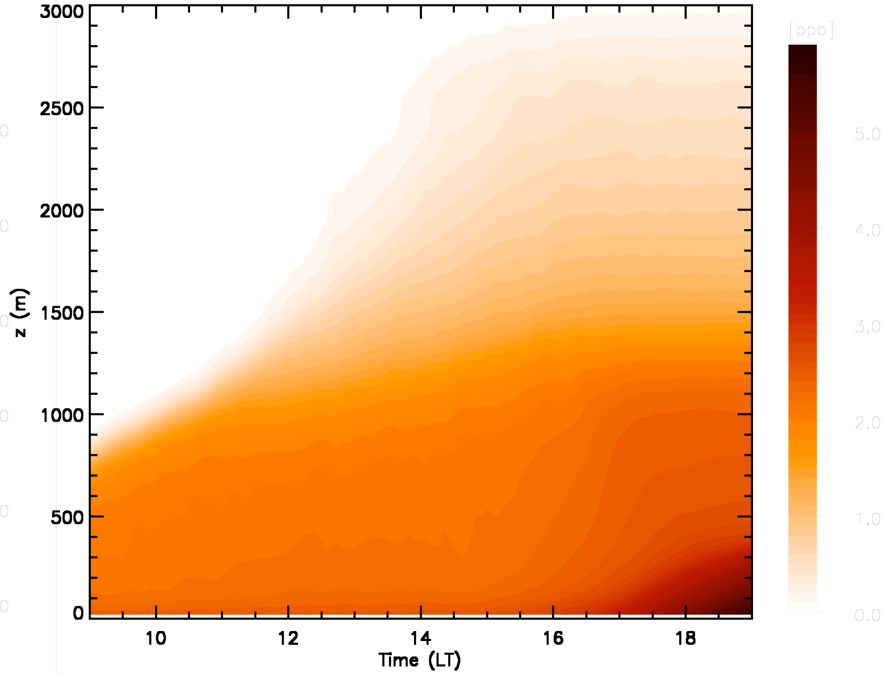
Same numerical experiment only reducing moisture content

Vertical profile evolution of an inert emitted scalar

Clear boundary layer



Cloudy boundary layer

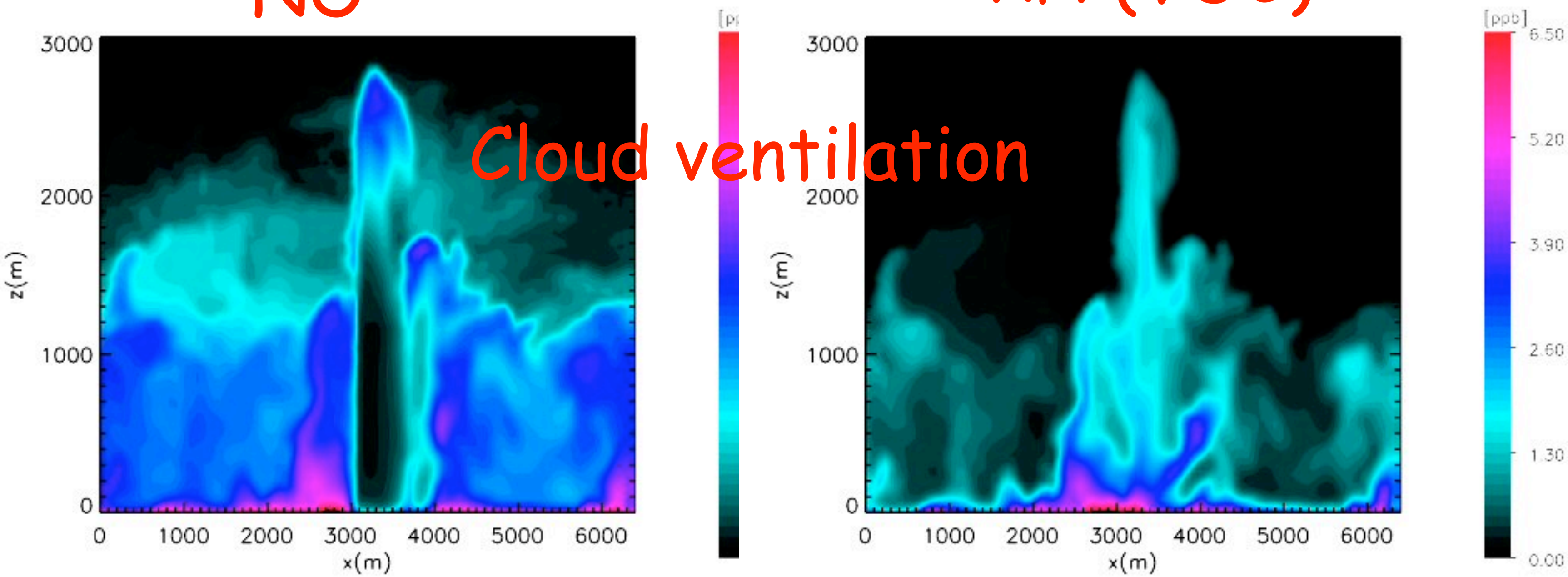


Enhancing the dilution

Vertical instantaneous cross section (LES simulation)

NO

RH (VOC)



Ventilation rates 0.5-1.5 ppb/hour

Stable Boundary Layer

-Refreshing the main characteristics SBL

- Dispersion

Properties

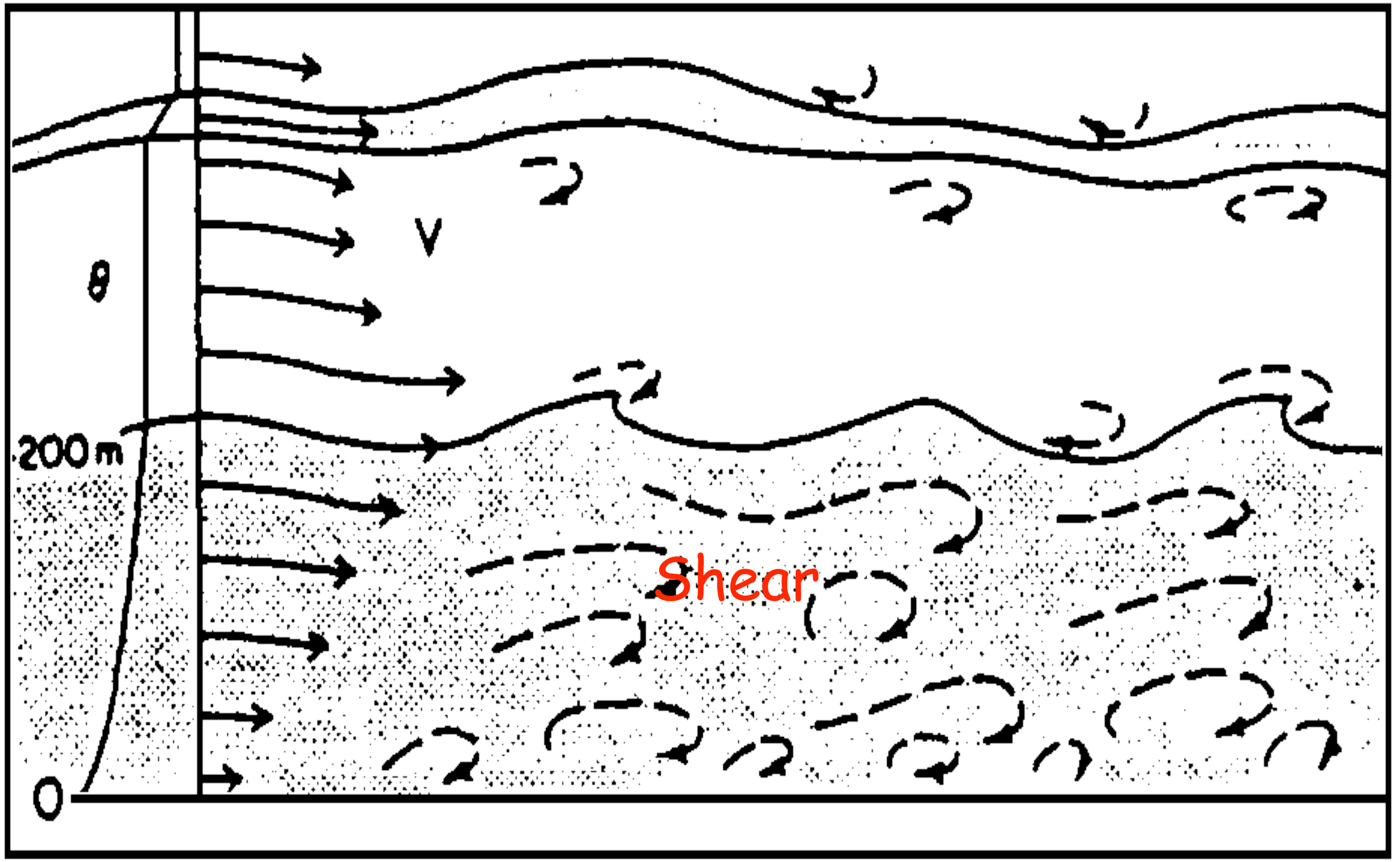
-Reactivity

Vertical transport

Turbulent mixing

Sketch of the SBL

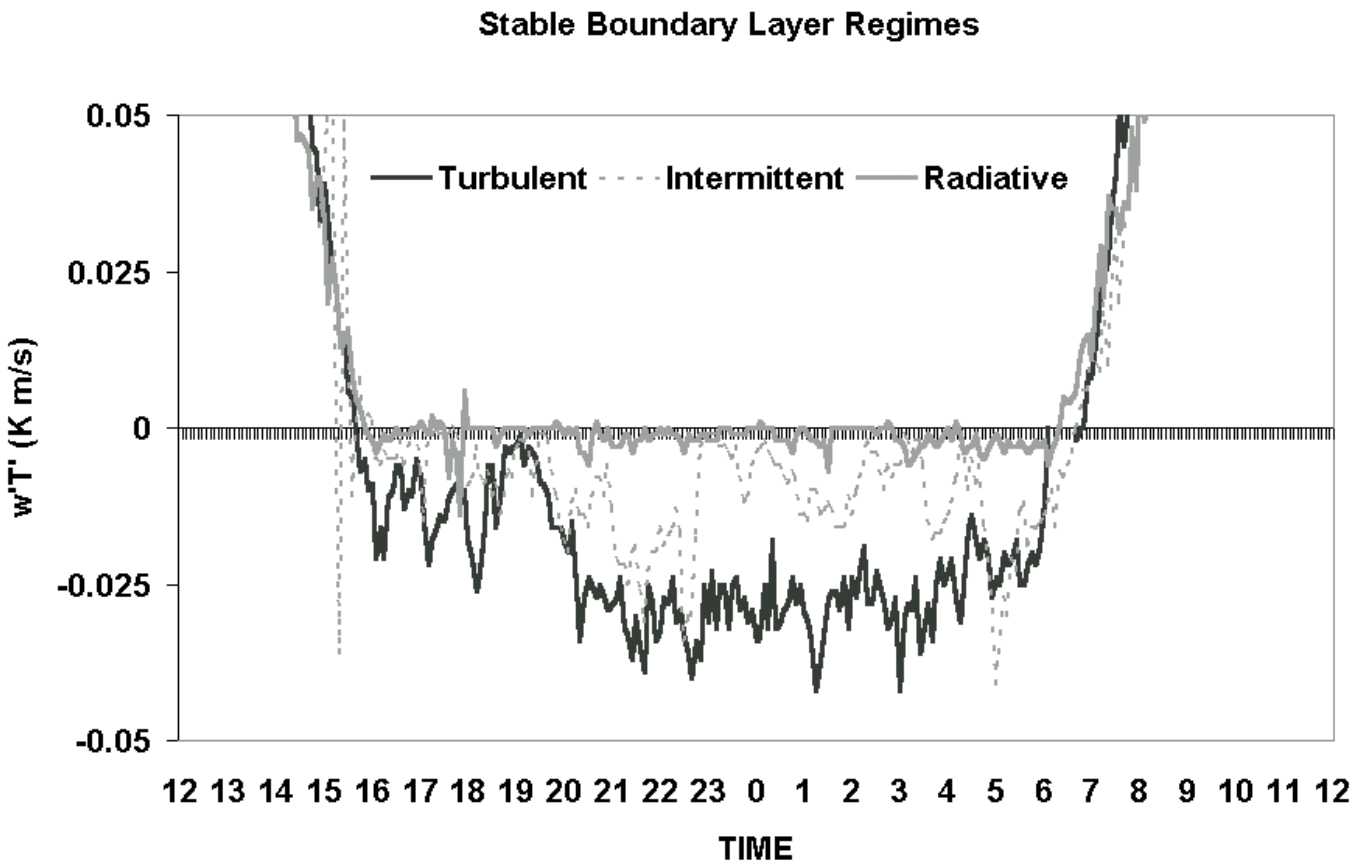
Influence mesoscale motions



Longwave radiative cooling at surface

Wyngaard (1992)

Classification of SBL depending of the levels of turbulence

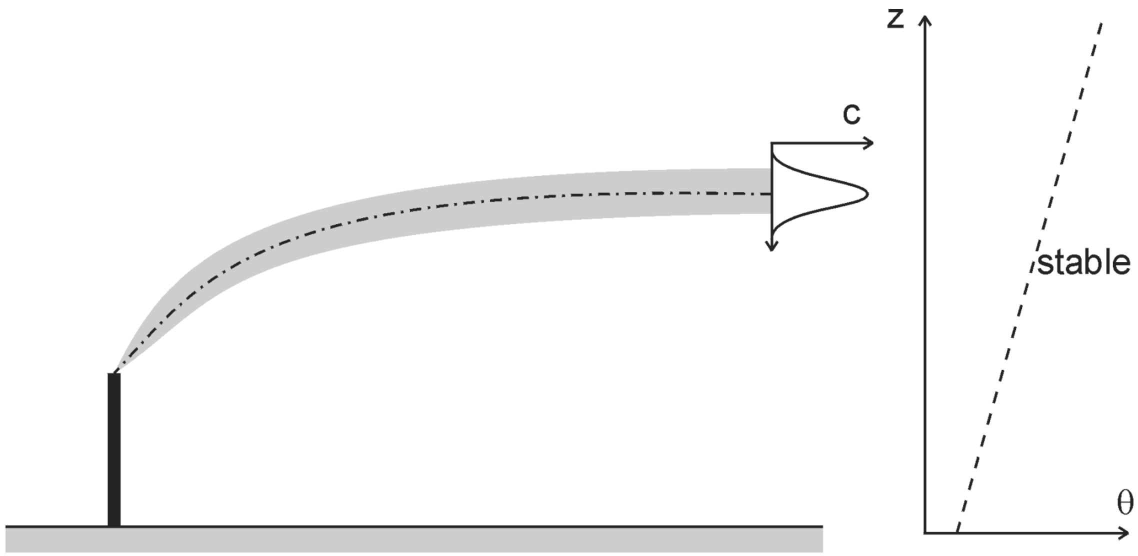


van de Wiel et al. (2002)

Effect on dispersion

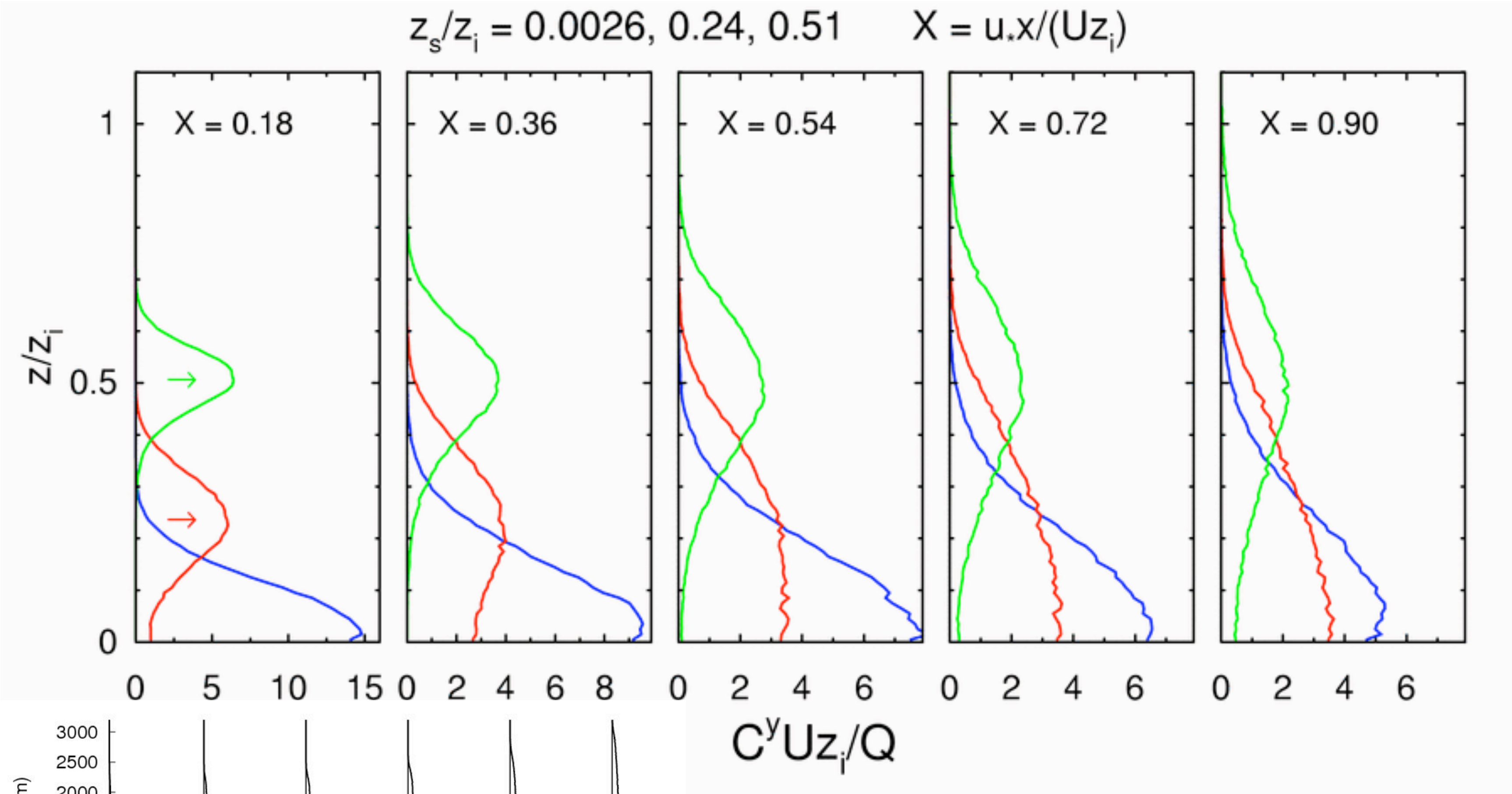
Vertical dispersion: fanning

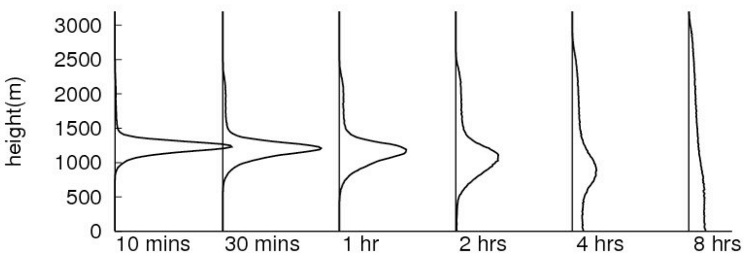
Lateral dispersion: meandering (wind shear)



Fanning (vertical dispersion)

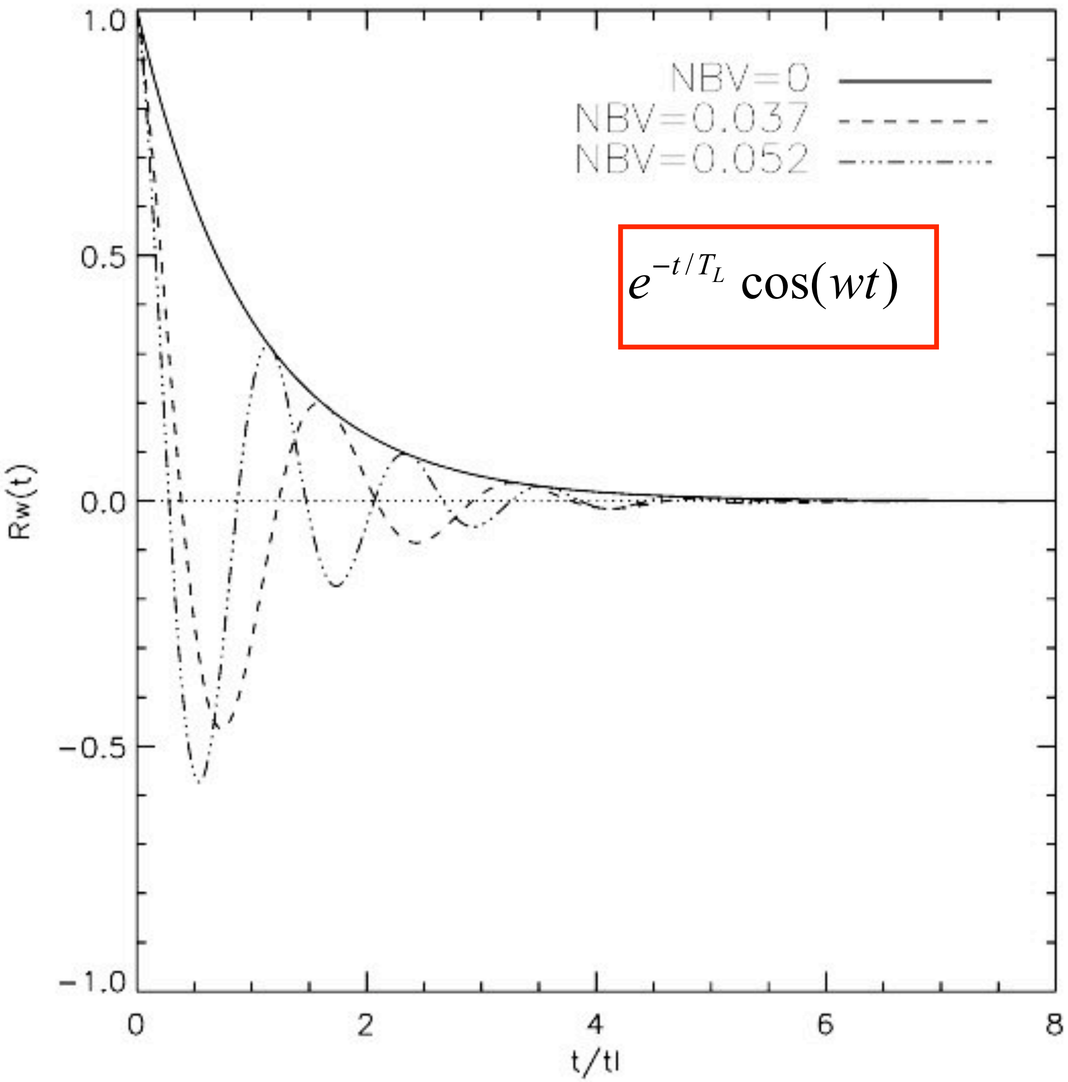
Profiles of Average Crosswind-Integrated Concentration (CWIC)





(Weil, Patton, and Sullivan, 2006)

Autocorrelation (vertical comp.)

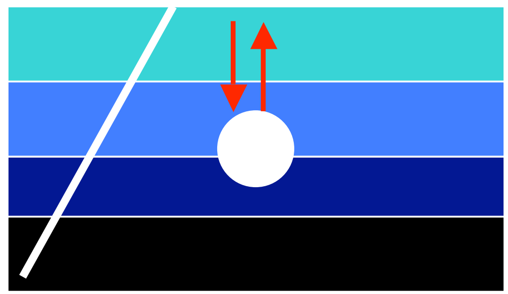


$$\sigma_j^{\,2}(T) = 2\overline{u_j^{\,2}}\int_o^T dt \int_o^t R_j(\tau)\, d\tau$$

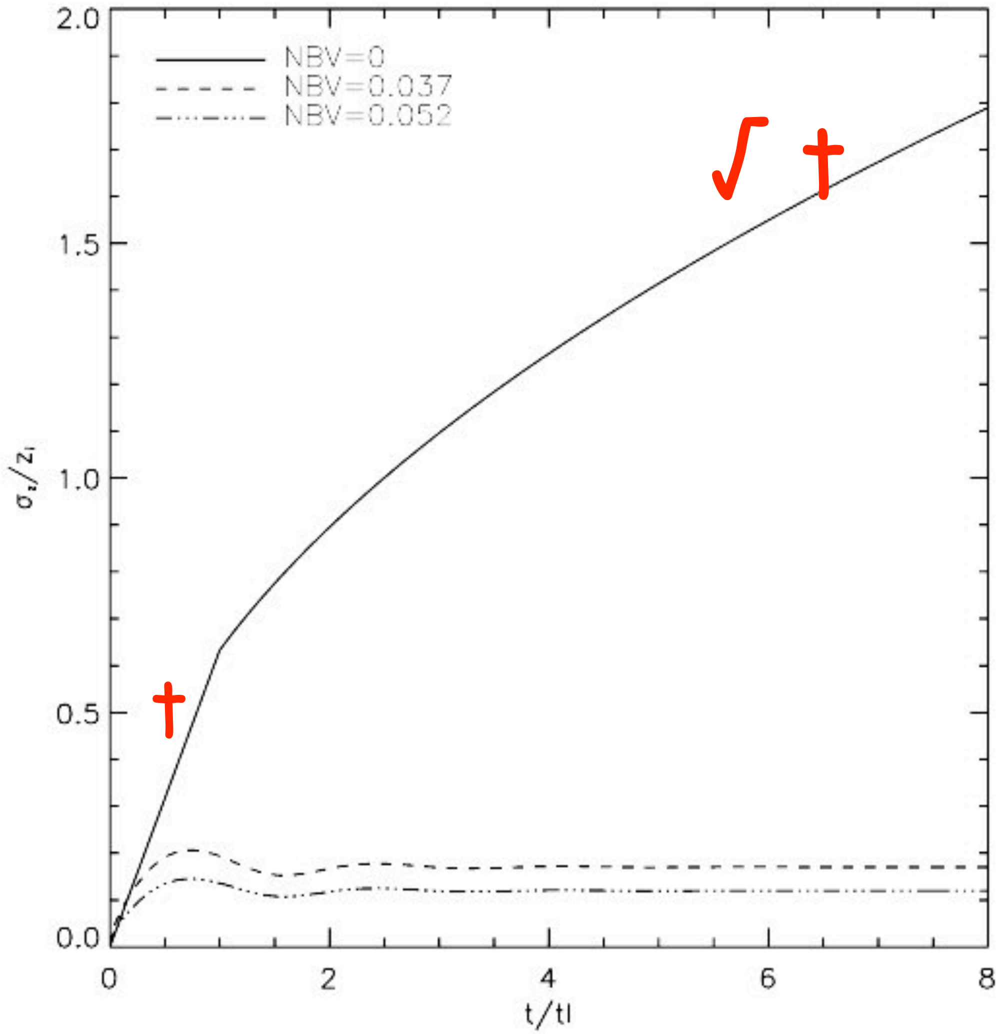
Period oscillation related to Brunt-Väisälä

$$N_{BV} = \left(\frac{g}{\overline{\theta}}\frac{\partial\overline{\theta}}{\partial z}\right)^{1/2}$$

$$\frac{\partial\overline{\theta}}{\partial z}$$



Vertical dispersion

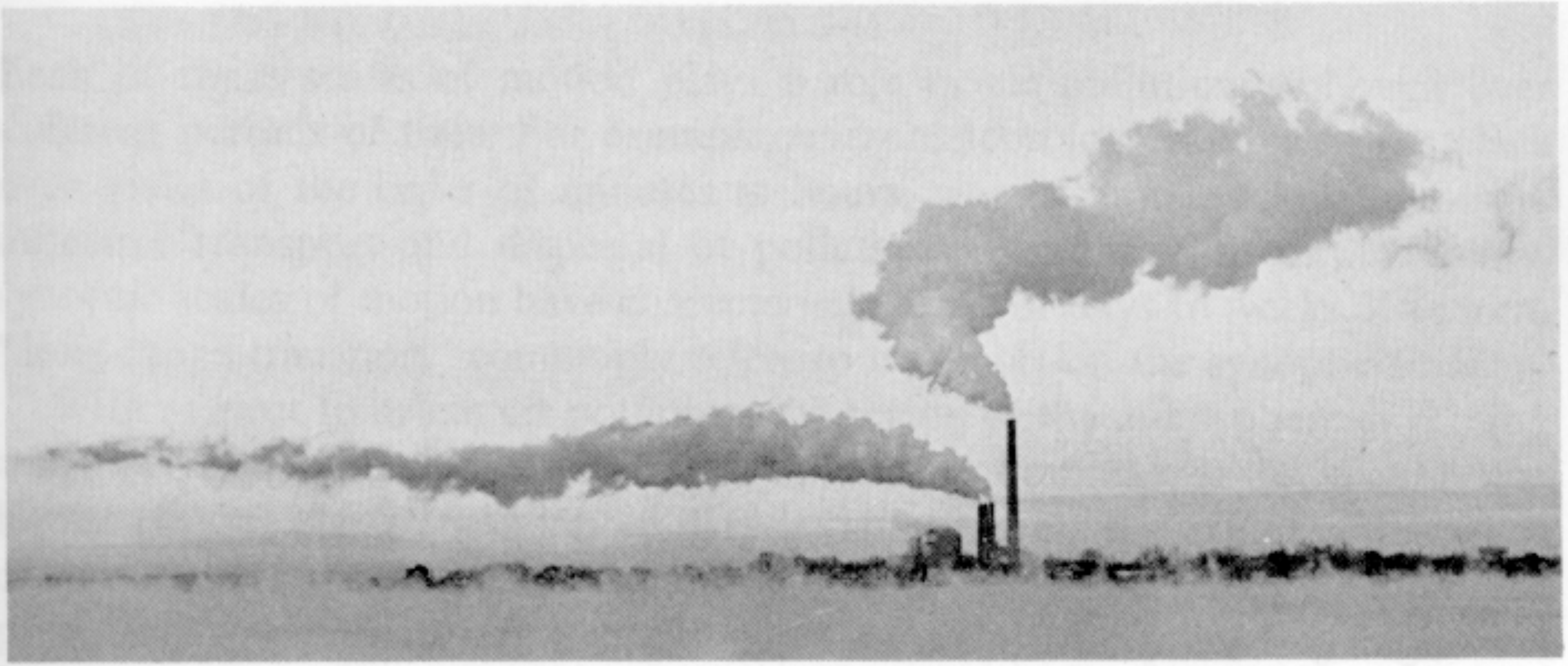


$$\sigma_j^{\ 2}(T) = 2\overline{u_j^{\ 2}} \int_o^T dt \int_o^t R_j(\tau) d\tau$$

(Anfossi et al., 2005)

Meandering (lateral dispersion)

(courtesy Jeff Weil)



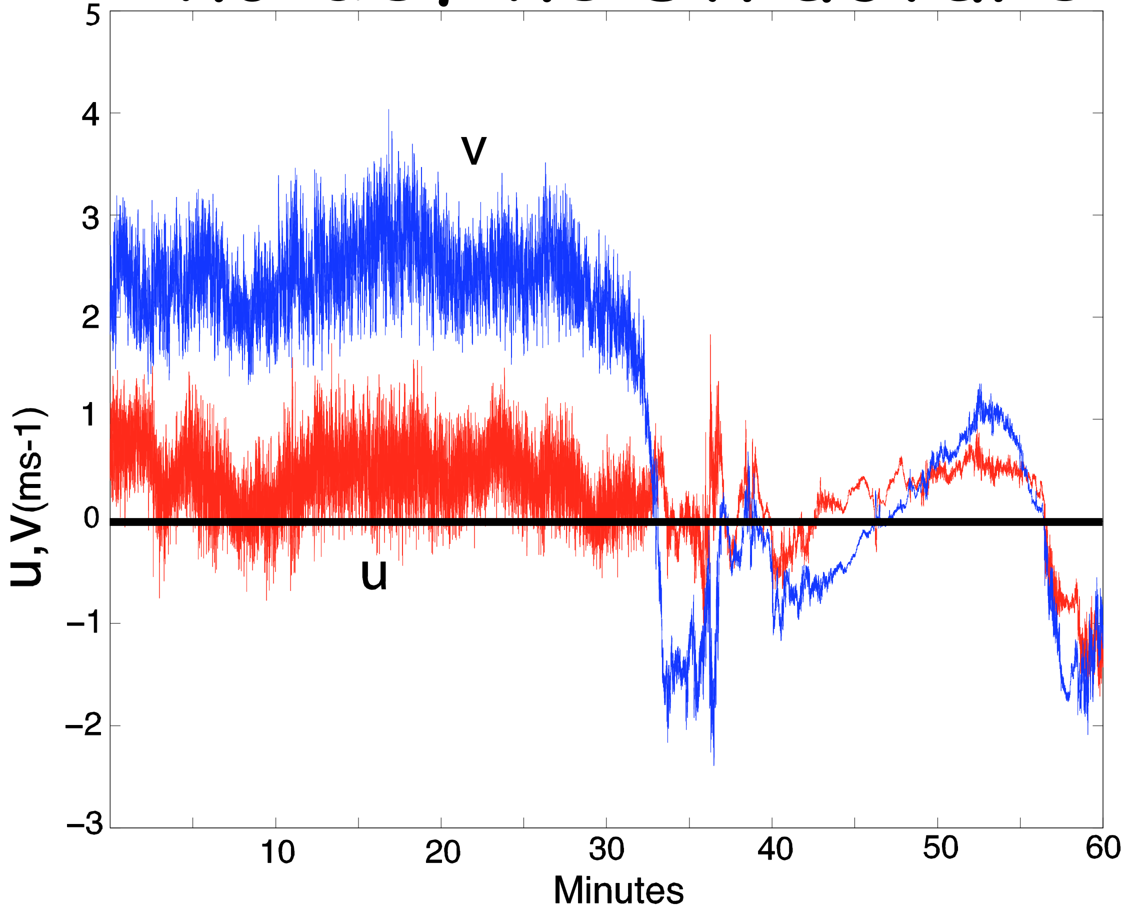
Meandering

Oscillation of the wind back/forth

Interaction of stable boundary layer dynamics and mesoscale motions

Multiple causes (density flows, internal gravity waves…)

Wind direction shifts: no define structure



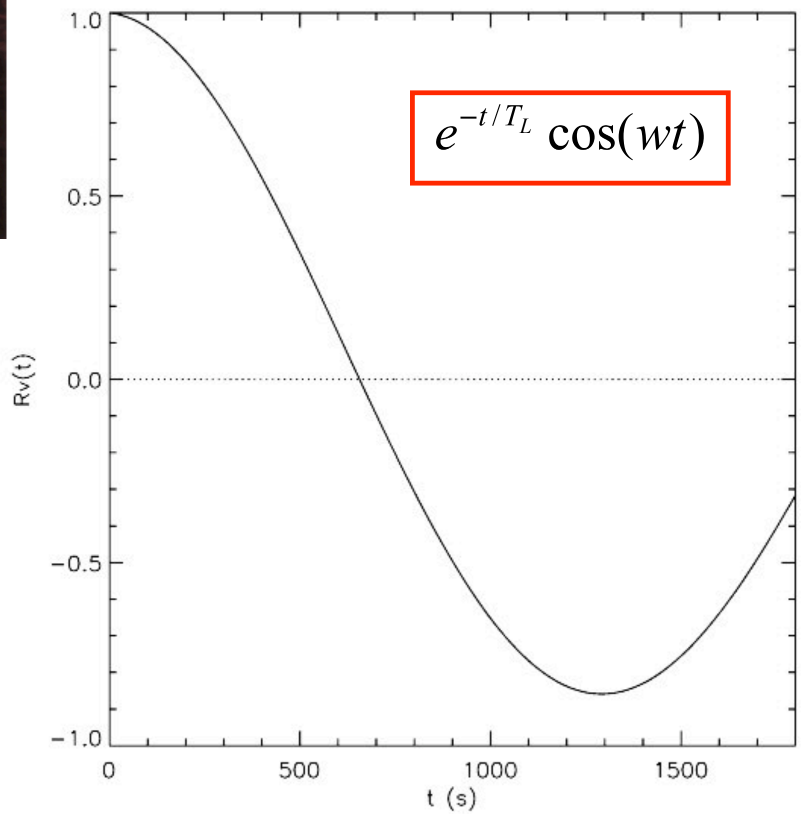
Mahrt (2008)

Autocorrelation (v-component)

Related to the variability of v!!!

Meandering period~30-60 min

(Anfossi et al., 2005)



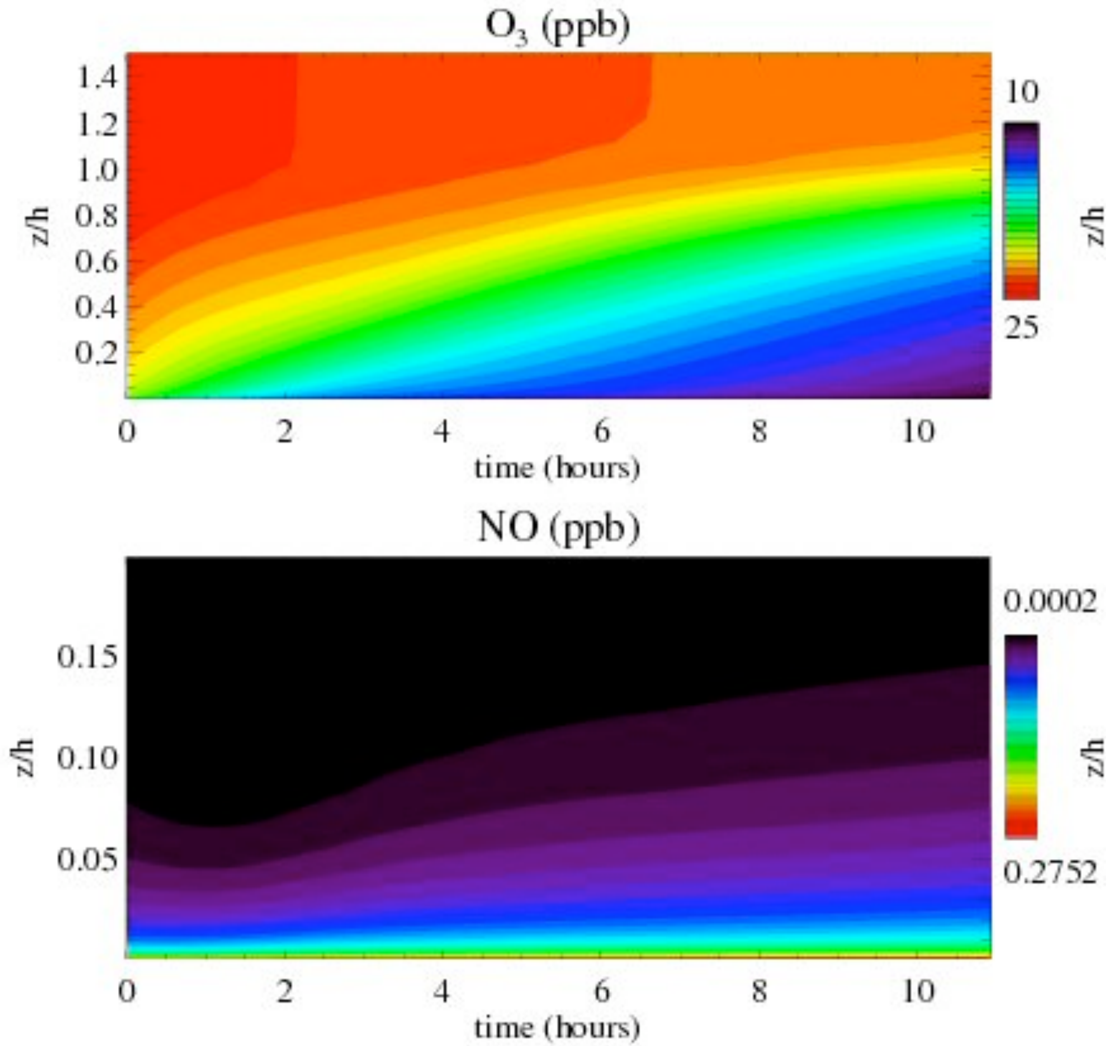
What about vertical transport and reactivity?

Stratification limits vertical transport

Stratification modifies reactivity

Intermittent events promotes exchange between residual layer and SBL

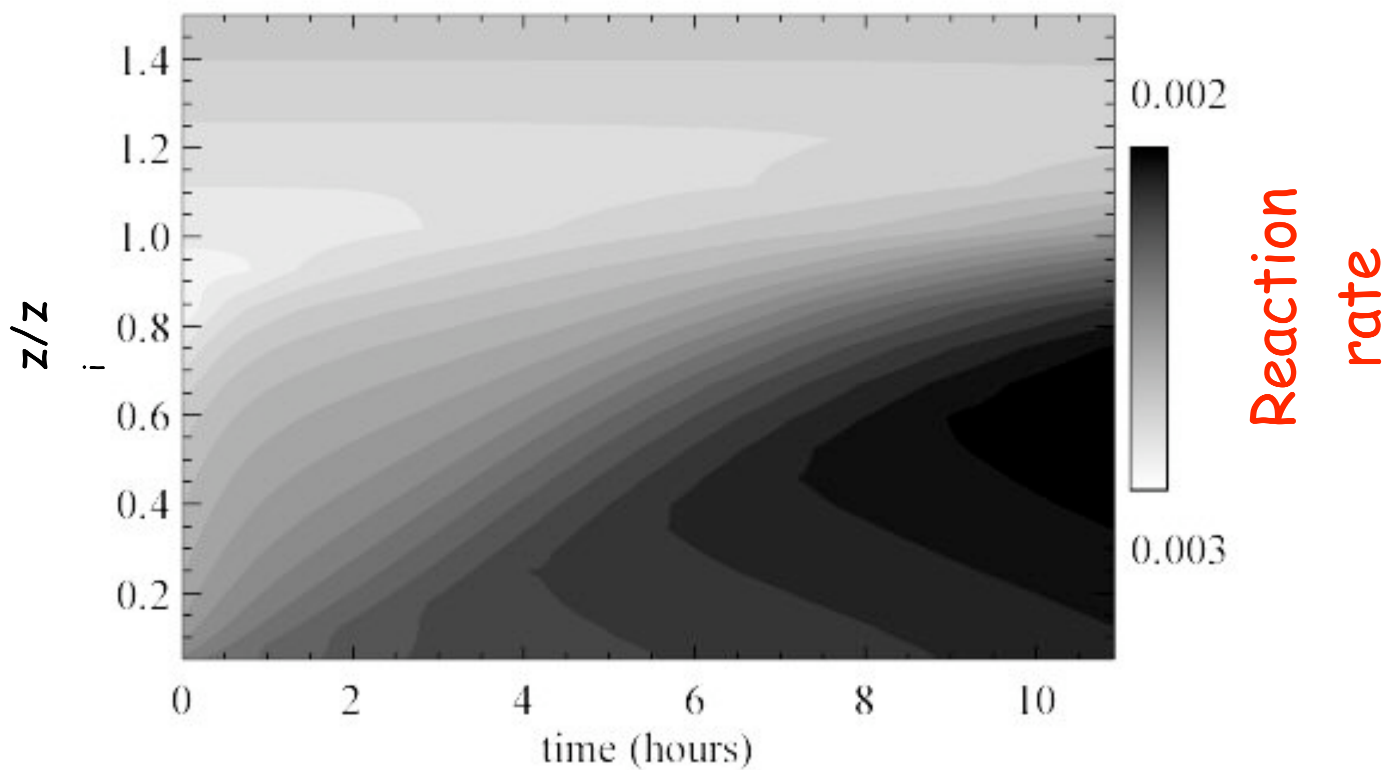
Evolution reactants during SBL (1D)



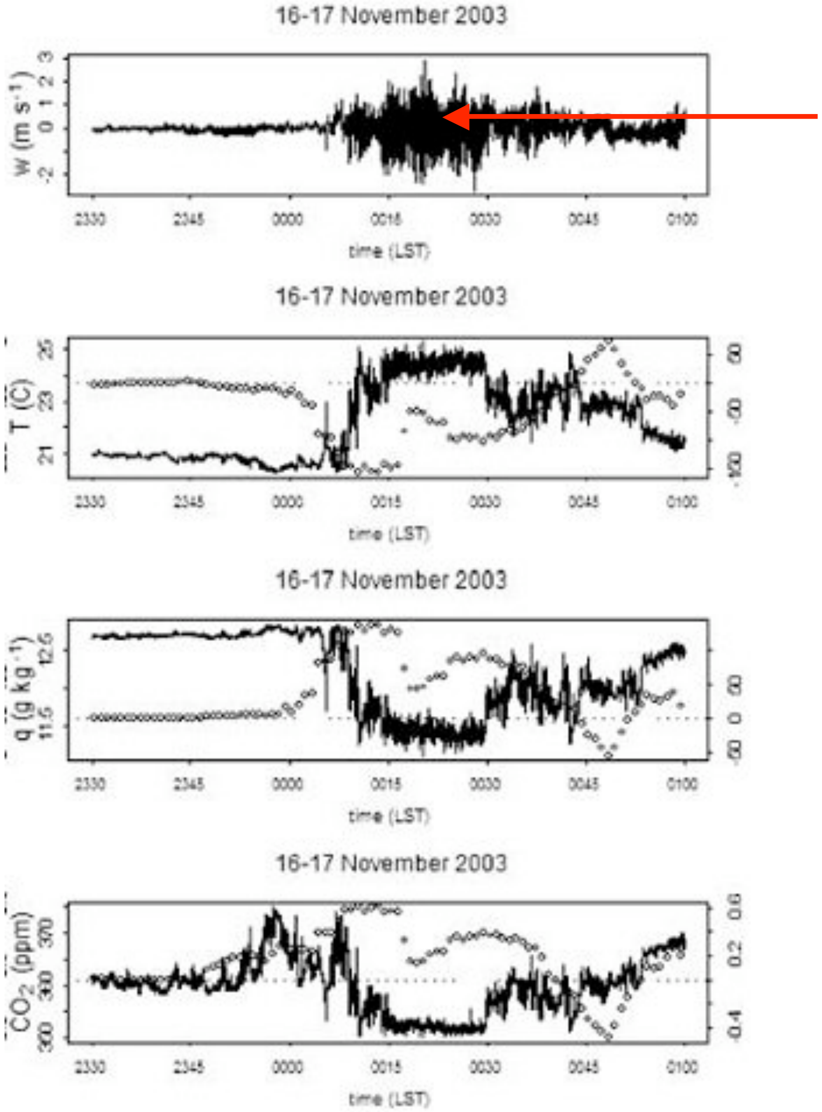
Stratification controls the turbulent mixing and therefore reactivity

Evolution of a reaction rate (1D)

Reaction rate depends on absolute temperature and turbulent mixing (segregation species)



Intermittent event: mixing air masses SBL and residual layer



Turbulent mixing is enhanced during intermittent event introducing air masses in the SBL characterized by:

Warm air

Dry air

Concluding remarks

Dispersion and chemical transformation in cloudy boundary layer clearly differs from the ones in dry CBL

Stratification limits vertical dispersion and chemical reactivity

Still a lot of open issues:

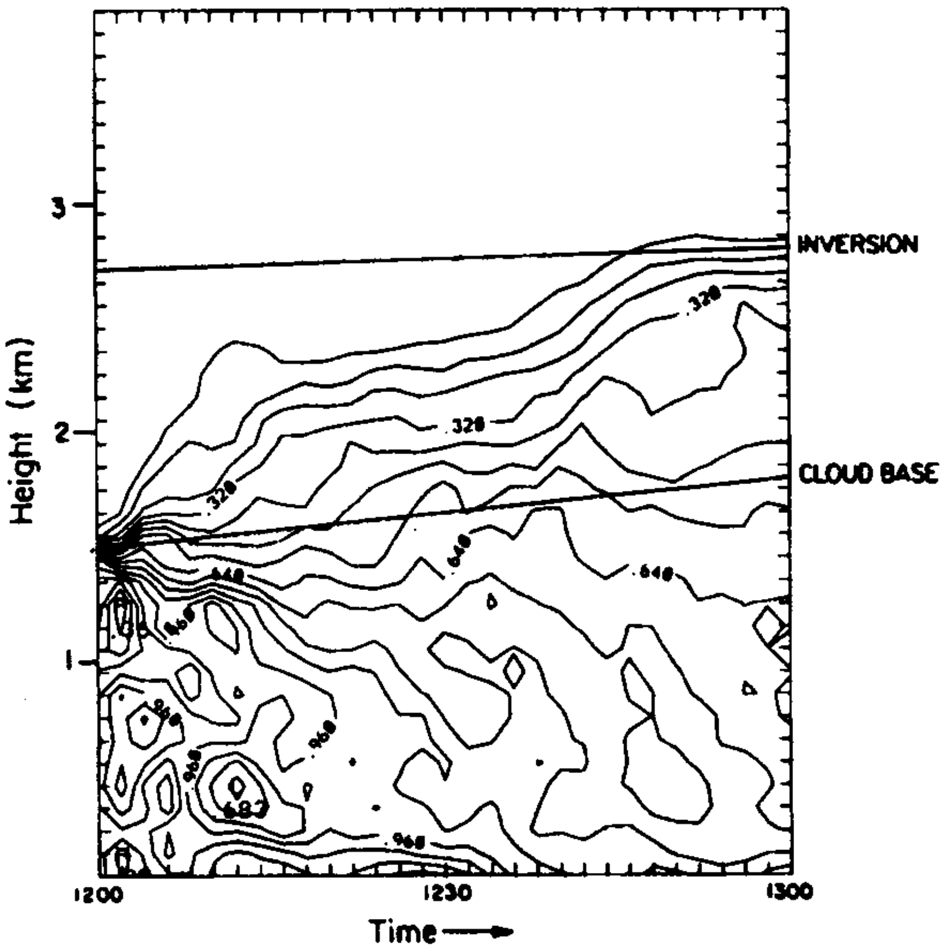
Ventilation of pollutants by clouds and slow dispersion in the cloud

Dispersion in SBL: meandering…

Role of clouds in influencing the chemistry in the nocturnal residual boundary layer

Intermittency events on SBL might promote the exchange reactants between SBL and

Dispersion in shallow cumulus
(Cotton et al, 1995)



Presence of clouds:

-Enhancement of the vertical transport

-Atmospheric compounds remain in the boundary layer (depending inversion strength)

Using LES to understand and obtain the statistical properties of plume dispersion

$$\sigma_j^{\,2}(T) = 2\overline{u_j^{\,2}}\int_o^T dt \int_o^t R_j(\tau)\,d\tau$$

Physical processes influencing chemistry

UV-Radiation

$$A \longrightarrow B + C$$ (1st order reaction)

Turbulence

$$B + C \longrightarrow A$$ (2nd order reaction)

Possibility to define a photostationary state

$$\varphi = \frac{kAB}{jC}$$

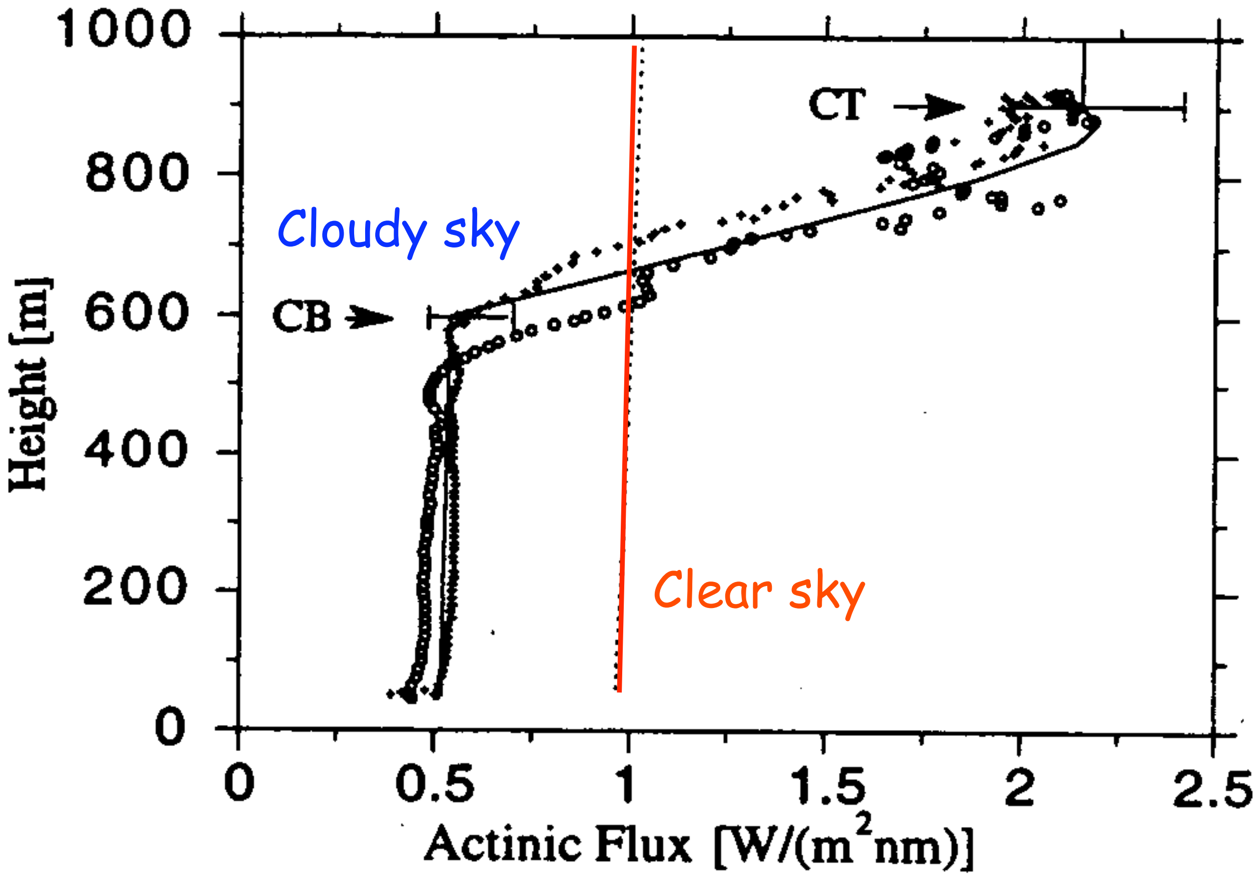
Influence of physical processes on chemical reactions

Photodissociation rate depends on the actinic flux in the UV spectral region.

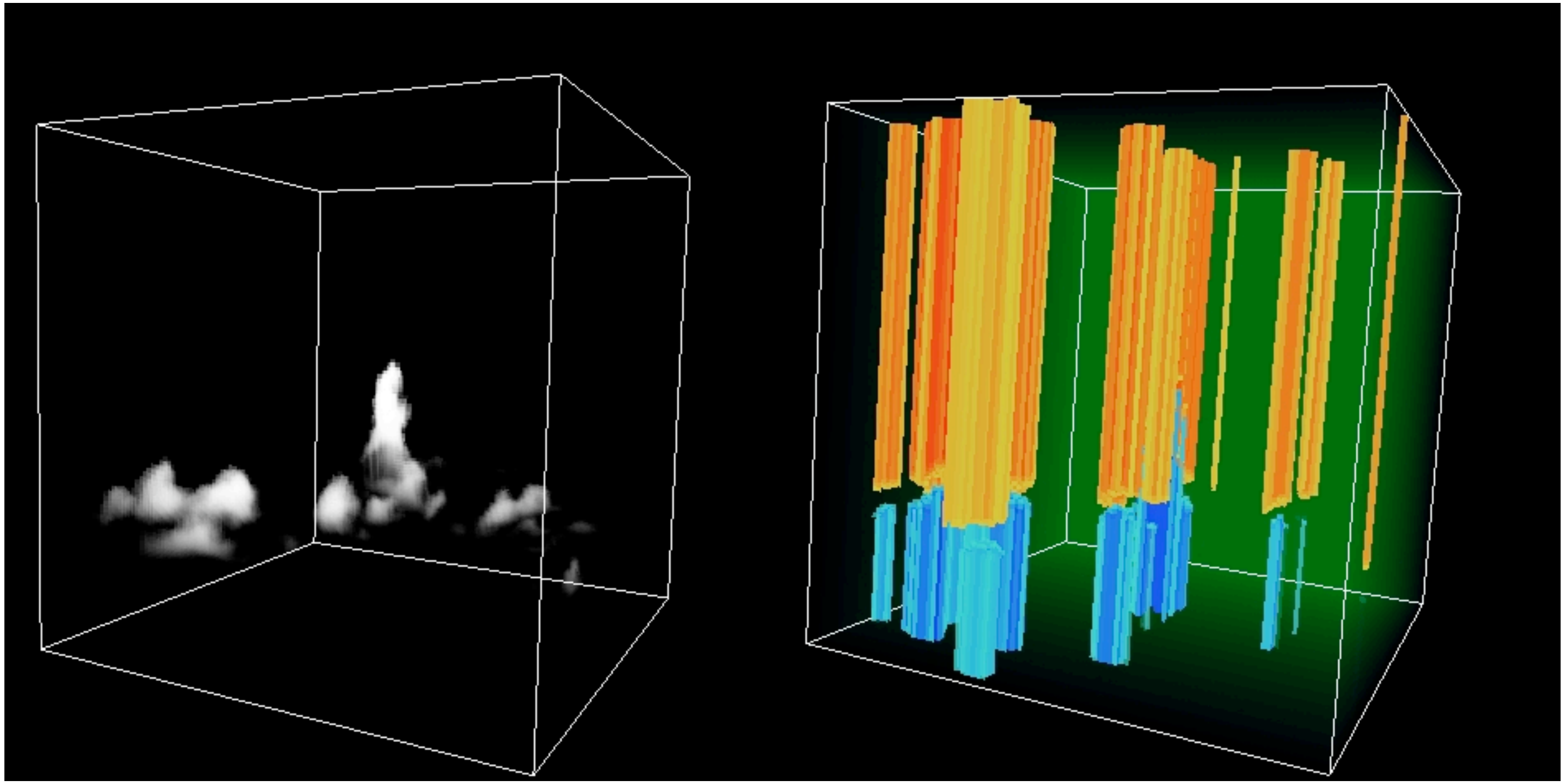
ACTINIC FLUX is largely perturbed by the presence of clouds

Vertical profile of actinic flux

Measurements collected during ASTEX (stratocumulus cloud deck)



Instantaneous vertical cross section photolysis rate (j)



Parameterization depends on:

- Cloud optical depth
- Cloud base and cloud top
- Solar zenith angle

Influence of physical processes on chemical reactions

Chemical reaction rate depends on the **efficiency of turbulence** to bring species together (non-premixed species are segregated)

Different turbulent structure and intensity inside the cloud and outside the cloud

Departure from chemical equilibrium

$$\varphi = \frac{kAB}{jC}$$